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THE "ITABIRITE" IRON ORES OF BRAZIL.

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In an article by Mr. Th. Gathmann,[1] on the so-called "itabirite" iron ores of Minas Geraes, Brazil, in the May number of the *Zeitschrift für Praktische Geologie* the writer cites evidence for, and attempts to prove, that these ores are secondary surface deposits formed by the leaching of silica from an iron-oxide bearing quartzite for which the term itabirite has been adopted. Mr. Gathmann admits that he has seen only a very small part of the district, in fact that his observations have been limited to an area a few kilometers square in a district which is several hundred kilometers in extent, and it happens, unfortunately, that this area is rather more complex geologically than most of the rest of the district, making it difficult to see the relation of the different formations to each other.

As a result of three years spent in exploration work, both surface and underground, in various parts of the Minas Geraes iron ore field, I have gained a different impression of the nature of the "itabirite ores" from that held by Mr. Gathmann; so that it seems well to record my observations and state deductions which I have drawn from them.

[1] Gathmann, Th., "Beitrag zur Kenntnis der 'Itabirit' Eisenerze in Minas Geraes (Brasilien)," *Zeitschrift für Praktische Geologie*, XXI. Jahrg., Mai, 1913, s. 234 bis 240.

It is my opinion that practically all the ores except the surface blanket of "canga" or iron ore conglomerate, the nature of which will be explained later, are metamorphosed forms of original sedimentary iron ore beds and lenses, and that they were not formed from itabirite by the leaching of silica, as is held by Mr. Gathmann. A general statement of this opinion has already been published.[1] Further evidence has been secured and this will be stated after considering briefly the nature and geologic relations of the ores.

NATURE OF THE ORES.

Itabirite, as has been stated, is an iron-bearing quartzite generally thinly laminated with alternating layers of quartz sand and iron oxide but locally consisting of a granular mixture of quartz sand and iron oxide. It is the principal constituent of the extensive Minas Geraes iron formation which occurs as a sedimentary layer, interbedded between a predominating quartzite formation below and a predominating schist formation above. The iron formation varies greatly in thickness, in places being less than 15 meters and elsewhere more than 1,500 meters thick. Besides itabirite it contains lenses and layers of bedded iron ore which occur interlayered with the itabirite. It also contains occasional beds of ferruginous schist. Beds and lenses of impure limestone occur in the upper part of the iron formation and in the lower part of the overlying schist.

Itabirite probably makes up more than 95 per cent. of the iron formation. It rarely contains less than 30 per cent. metallic iron and from this it grades up, with diminishing quartz sand, into ore the lower limit of which may be taken as 50 per cent. metallic iron. Occasionally itabirite, very low in iron, apparently grades down into ferruginous sandstone or quartzite.

When iron formation weathers at the surface a blanket consisting of a mixture of itabirite and ore fragments cemented by limonite is formed. This blanket may vary in thickness from a

[1] Leith, C. K., and Harder, E. C., "The Hematite Ores of Brazil and a Comparison with the Hematite Ores of Lake Superior," ECON. GEOL., Vol. VI., No. 7, Oct.–Nov., 1911, pp. 670–686.

few centimeters to more than 15 meters and spreads over the surface of the iron formation as well as over the surface of adjacent formations such as schist or granite. This is the iron ore conglomerate or breccia termed "canga."

The so-called "itabirite ores" of Brazil are therefore of two distinct classes: (1) those occurring as original beds or lenses in the iron formation and (2) those resulting from the weathering and concentration of the iron formation. They may be classed as follows:

Original or bedded ores.
- Hard massive ore.
- Soft powdery ore.
- Laminated or thin bedded ore.

Concentration ores.
- Canga (iron ore conglomerate).
- Stream sand and gravel ores.
- Rubble ore.
- Enriched itabirite.
- Leached carbonate.

Of the above classes the bedded ores are by far the most important, especially the hard massive ore. This is of high grade and is the only type of ore which is being considered at present in plans dealing with the development of the Brazilian iron industry. The soft powdery ore is also of high grade, but on account of its consistency it is at present considered undesirable. The laminated ore is of lower grade than either of the other types of bedded ore. However, there occur in different parts of the district enormous deposits of this ore which will ultimately be of great importance.

Of the concentration ores the canga is the only type of importance. While the canga blanket covers many square kilometers, its grade is such that it cannot be considered desirable for the iron industry for many years to come.

Below are given the average range in iron and phosphorus content of the principal types of ore, assuming 50 per cent. metallic iron as the lower limit for iron ore.

	Iron, Per Cent.	Phosphorus, Per Cent.
Hard massive ore	69 to 70	.003 to .020
Soft powdery ore	50 to 69½	.004 to .05
Laminated ore	50 to 68	.003 to .07
Laminated ore (hydrated)	63 to 67	.05 to .3
Canga	50 to 65	.1 to .3

The hard massive ore is hematite, generally dense or finely specular but occasionally, where strongly metamorphosed, it is coarsely crystalline and has an admixture of magnetite. It occurs in beds varying up to more than 150 meters in thickness and to more than a kilometer in length. Hard ore rarely contains more than 1 per cent. of silica and its metallic iron content is remarkably constant.

The soft powdery ore is specular hematite in a fine friable form, so that most of it when dried crumbles to dust which will pass through 100 mesh. Hard ore and soft ore frequently occur intermixed with each other, lenses or irregular bunches of soft ore occurring in hard ore beds or irregular masses of hard ore occurring in soft ore deposits. Soft ore deposits are in general much smaller and more irregular than hard ore deposits. Both occur as lenses or beds interlayered with itabirite or laminated ore.

Laminated ore consists of earthy to specular hematite. It is friable and breaks up into thin plates parallel to the lamination. It is also quite porous allowing free circulation of ground water, on account of which large portions of these deposits are hydrated, especially near the surface, and consist of a mixture of hematite and limonite. Unhydrated, laminated and soft powdery ores grade from almost pure iron oxide, with little or no quartz sand, down to itabirite with more than 30 per cent. silica. The line between itabirite and ore in these cases is purely artificial. In the hydrated portions of the laminated ore deposits the silica has generally, in large part, been removed, so that although somewhat lowered in grade by the hydration, its silica content is generally small and the ore is fairly constant in grade.

Unhydrated ores of various types and even itabirite contain a very small percentage of phosphorus. It appears that phosphorus

becomes concentrated during the hydration, either being brought in from the outside or remaining while other materials are being removed. Ore hydrated to beyond 2 per cent. combined H_2O increases rapidly in phosphorus content. The hydrated portions of laminated ore deposits rarely go to a greater depth than 20 or 25 meters except along occasional more porous layers.

Surface weathering has but little effect on hard ore and soft powdery ore. The former is sometimes slightly hydrated along cracks, for a few centimeters from the surface, while the latter is generally altered to canga to a depth of 4 or 5 meters and below this somewhat hydrated for an additional meter or two. The laminated ore is affected to a greater depth by surface agencies, and along with the hydration there is removal of silica. This, however, rarely is sufficient to make an ore out of an itabirite, so that but a small percentage of this material can be classed with the concentration ores.

Canga consists of material derived by weathering from the iron formation. The canga blanket is generally thin along the top of the iron formation ridges and thick on the lower slopes, due to material being transported down the slopes and deposited near the base. Where iron formation hills rise above the bordering schist or granite areas the canga blanket extends out over these areas. The best grade of canga occurs on the iron formation areas, especially where ore occurs with the itabirite. Frequently such canga is made up, to a large extent, of irregular fragments of ore cemented by limonite and hydrated hematite. The canga overlying areas of other rocks is of lower grade than that overlying iron formation areas, containing a large proportion of impurities such as clay (perhaps containing bauxite, etc.) and silica. The farther away from the iron formation, the poorer is the canga until finally it becomes merely an ocherous clay. Over and close to iron formation areas the fragments in the canga are usually angular, farther away they are small and rounded and finally they disappear. Thus there is every gradation of canga, from ferruginous clay to iron ore with 65 per cent. metallic iron.

Of the other classes of concentration ores the only ones of importance are rubble ores and leached itabirite.

Rubble ore deposits occur as talus under extensive outcrops of hard ore. They are simply masses of hard ore fragments broken off from the outcrops, and are of the same grade as the bedded hard ore from which they are derived.

Where canga overlies compact thin-bedded itabirite it frequently retains the itabirite texture though most of the silica is removed. This canga in situ, exhibiting original textures, is rarely more than a meter or two in thickness, being underlain by sandy itabirite. It is leached itabirite.

Stream sand and gravel consisting of hematite occur along some of the streams cutting through the iron formation belts. They are rarely pure enough to be called ore.

Leached carbonate is an earthy material consisting of hydrated iron or manganese oxides, or a mixture of the two. It is derived from the decomposition of impure limestone beds occurring in the upper part of the iron formation and in the lower part of the overlying schist. It is seldom rich enough in iron to be called ore.

EVIDENCE FOR ORIGINAL DEPOSITION.

Evidence to prove that bedded ores are original deposits and not secondary deposits formed by the leaching of silica from itabirite are:

1. Bedded ore deposits are in the form of beds and lenses interstratified with itabirite. Ore beds and itabirite beds have the same strike and dip and are perfectly conformable. Itabirite, with abundant silica, frequently outcrops at the surface at the contact with hard ore of 69 per cent. metallic iron and both keep their consistency with depth. Where the dip is shallow, hard ore beds frequently form cliffs on hillslopes as quartzite or limestone beds would, and here itabirite may be seen both above and below the ore bed. On Caué Peak, near Itabira de Matto Dentro, a bed of hard ore, having a maximum thickness of about 110 meters, forms a cliff outcrop for over a kilometer along the hillslope until it gradually pinches out. (See Fig. 39.)

In tunnels and shafts driven across the bedding of iron formation are frequently seen itabirite, soft powdery ore, hard ore and even laminated ore interstratified with each other. The same

FIG. 39. Caué Peak near Itabira de Matto Dentro looking north. Shows iron ore bed forming cliff with itabirite above and below.

thing may be seen on the slopes of deep valleys cut into the iron formation. In the Esmeril Grota, near Itabira de Matto Dentro, a deep, steep-sided gorge, cutting across the iron formation trans-

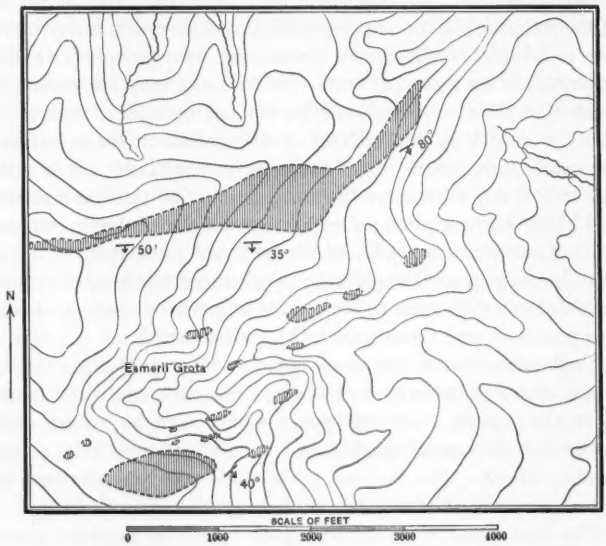

FIG. 40. Iron Ore Lenses on Esmezil, Itabira de Matto Dentro. Contour interval, 25 meters.

versely to the strike, beds of ore not more than two meters in thickness continue for several hundred meters along the side of the gorge with itabirite above and below. (See Fig. 40.)

On a horizontal plane the ore deposits are in the form of lenticular areas with the longer diameter in direction of the strike of the formation. (See Fig. 40.) The areas vary in width and are in places continuous for long distances along the strike, while elsewhere they pinch out and come in irregularly. Structurally therefore they behave in every respect as beds of limestone or sandstone would.

2. Limestone beds are frequently associated with itabirite beds, and occasionally layers of limestone and itabirite are interstratified and outcrop together at the surface. In some places they are interlayered, in fine laminae, and frequently hematite flakes and quartz grains occur disseminated in the limestone. Such associations show without reasonable doubt the original nature of the itabirite. In one or two cases I have seen thin beds of iron ore interlayered with limestone in the same manner as the itabirite, but on a smaller scale. It does not seem reasonable to think that the iron ore should be derived by alteration from a sandy iron rock by the leaching of silica, while at the same time the much more soluble limestone remains unaltered. It is difficult to find any alternative from the assumption that the itabirite and iron ore are original sediments deposited with the limestones, schists and quartzites with which they are associated.

3. In underground exploration work there has been shown to be a distinct difference between ores affected by surface alteration processes and those unaffected by the same.

Exploration work has been done under my charge, in the region east of the Serra do Caraça, during the last three years. Up to the present, a total of 737.65 meters of underground work has been done, consisting of shafts, tunnels and drill holes to the number of 28. The deepest shaft sunk was 36.50 meters in depth; the longest tunnel driven was 98.70 meters in length.

The exploration work has been done mainly in localities where surface outcrops are indistinct due to the fact that the under-

lying ore or itabirite is medium soft. Hard ore usually outcrops boldly at the surface and has been shown by topographic features to continue with depth. The problem, therefore, was to determine to what extent the nature of the underlying material might be judged from surface appearances in cases where the ore or itabirite does not form distinct outcrops.

It was found in general, that the exploration work penetrated first a layer of surface altered material of varying thickness, depending on the location of the shaft or tunnel. On the summits and upper slopes of the ridges, the blanket of surface altered material was found to be thin, while on the lower slopes where canga accumulates, it was found to be of considerable thickness. This surface layer consists in places of canga and elsewhere of hydrated laminated ore or of leached itabirite, depending more or less upon the nature and consistency of the underlying material. On the lower slopes of the ridges, canga is the principal constituent of the surface blanket, while on the upper slopes it may consist of canga, hydrated laminated ore or leached itabirite.

Where the underlying material is very soft, there canga usually forms on the surface, irrespective of whether this underlying material is soft powdery ore or soft itabirite. Where medium hard laminated ore exists underneath it will become hydrated at the surface but will retain its structure, while hard itabirite will become hydrated and be leached of its silica. Itabirite and laminated ore may be hydrated to a depth of 20 or 25 meters but the removal of appreciable amounts of silica goes to a depth of only a few meters; though presumably there must be some leaching of silica as far down as the hydration goes.

Below the blanket of strongly hydrated material there occurs fresh itabirite or ore which contains occasional hydrated beds, that because of their greater porosity, have given more easy access to circulating waters. With depth these hydrated layers gradually become less numerous.

The wholesale leaching of silica, assumed by Mr. Gathmann, seems to me to be very improbable. I have found high grade ore at a depth 36 meters below the surface with every indication

that it may continue downward indefinitely, and be affected only by such changes as may be expected from original deposition. It is difficult to explain on his hypothesis why silica should be completely leached out to such depths in some places while in other places, where surface and structural conditions are identically the same, itabirite with 50 per cent. or more of silica and not more than 35 per cent. of iron, should occur within a few meters from the surface or even at the surface.

Even more difficult of explanation by the leaching hypothesis, is the fact that some tunnels and shafts penetrated considerable thicknesses of sandy itabirite and below this encountered high grade ore, while others encountered alternating beds of itabirite and ore. Such occurrences point strongly toward a difference in original deposition.

Occurrences cited by Mr. Gathmann where tunnels driven beneath hard ore outcrops have encountered soft, sandy material, are easily explained as due to the lenslike nature of the ore bodies. Very frequently lenses of hard ore are only a few meters in diameter; in fact some have a diameter not much greater than their thickness, and are surrounded by soft ore or itabirite. Conclusions can be drawn from such occurrences only after a thorough examination of surface outcrops to judge their continuity.

SUMMARY.

From the various evidences cited, the conclusion appears to be reasonable that itabirite and the associated iron ore are original sedimentary rocks, formed partly by mechanical and partly by chemical or perhaps biological deposition. The association of limestone, quartzite and schist with itabirite, and of the latter with iron ore, always as lenses or interbedded layers, strongly suggests a similar origin for all of these formations. Such wholesale leaching of silica to great depths as would be necessary for the formation of these ores by secondary surface action, seems improbable, especially when it is considered that what has happened to the ore has also happened to the interlayered itabirite and other associated rocks. The numerous outcrops of limestone

in the district bear evidence that such extensive surface solution and decomposition are not widespread. It might be said that the localities where the ore occurs may be topographically and structurally favorable to surface action, but there are localities in which the same structural and topographical conditions prevail, yet, where at one place ore is found to a depth of 35 meters or more, while at another, sandy itabirite occurs directly underneath the canga within a meter or two from the surface.

The question, as to whether the iron ores of Minas Geraes are the result of original deposition or of surface concentration, is one of great practical importance. If the ores are the result of surface weathering agencies, then they can not be expected to go to any great depth, except perhaps along important water channels such as have been found to occur in some of the deposits of the Lake Superior district. If on the other hand they are the result of original deposition, then the depth to which they might continue is indefinite, and the changes to be expected are only such as would result from processes affecting original sedimentation. The facts seem to me clearly to prove the latter view.

THE OCCURRENCE OF ALUMINUM HYDRATES IN CLAYS.

M. G. EDWARDS.

The decomposition of rocks by ordinary processes of weathering results in the removal of certain constituents leaving an insoluble residue consisting essentially of silica, alumina, ferric oxide and combined water. This insoluble residue is called clay when kaolinite predominates and laterite when the hydrates of alumina and iron predominate. There are then two types of alteration to be considered here, kaolinization and lateritization.

Kaolinite is the most important of the hydrous aluminum silicates comprising clay and it so closely approximates the average composition of this group that it is designated commercially as the clay base. It is the chief residual product of feldspathic decay. Kaolin is in general believed to be the end product of rock decomposition in northern climates.

In the lateritic type of alteration, the end products of rock decay are aluminum hydrates and limonite. The aluminum hydrates occur as diaspore, $Al_2O_3 \cdot H_2O$, bauxite, $Al_2O_3 \cdot 2H_2O$, and gibbsite, $Al_2O_3 \cdot 3H_2O$. Laterite is generally regarded as the ultimate product of rock decomposition in tropical and semi-tropical latitudes. Due either to physical or chemical causes or both, kaolinization under tropical conditions yields to lateritization as the ultimate type of alteration.

There is considerable diversity of opinion regarding the relationships between kaolinization and lateritization, particularly as applied to the possibility of the formation of aluminum hydrates in temperate climates. Ries[1] admits the possibility that in some highly aluminous kaolins some aluminum hydroxide such as bauxite or gibbsite might be present. Hilgard says:[2]

[1] H. Ries, "Clays, Occurrence, Properties and Uses," p. 202.

[2] E. W. Hilgard, "Soils," p. 389.

"Aluminic hydrate is alone capable of explaining the presence of more Al_2O_3 than SiO_2 in easily soluble form excepting the relatively rare minerals of the allophane, collyrite and miloskite group and the visible occurrence of bauxite in modern formations renders this a perfectly simple and acceptable explanation. Since these minerals are known to be incapable of crystallization we are led to the assumption that they will as a rule be found in the finest portion of the soil, viz., in the "clay" of mechanical analysis."

On the other hand Lindgren says:[1]

"Little or no hydroxide of aluminum forms in ordinary weathering. Cameron and Bell state that during an examination of several thousand soils from all parts of the United States hydroxide of aluminum was observed in only one sample which came from southern California. The occurrence of bauxite is a rarity in the temperate region. In the tropical countries the deep residual soil (laterite) very often contains aluminum hydroxides."

The present investigation was begun in connection with a series of katamorphic studies in the metamorphic laboratory of the University of Wisconsin with a view of investigating by a statistical study of clay analyses the extent to which aluminum hydrates are present in the clays of the United States. Definite results of such an investigation must have some bearing on the nature of the conditions under which aluminum hydrates develop and may give some suggestion as to whether or not laterite results directly from the alteration of the parent rock or whether kaolinization represents the first stage in the alteration, followed by desilication of the stable mineral, kaolinite.

DATA AND METHOD OF INVESTIGATION.

As mineralogical descriptions of clays based upon rational analyses are obviously incomplete, the best available method of investigating the mineral composition of a clay is by a recalculation of the chemical analysis. The statistics which have been compiled are based largely upon analyses given in clay reports and bulletins published by the various state surveys and by the United States Geological Survey.

[1] W. Lindgren, "Mineral Deposits," p. 327.

One of the difficulties of this method of estimating the percentages of aluminum hydrates in clays lies in the fact that the analyst has generally, though fortunately not always, failed to differentiate between the free and the combined silica. In almost all clays sand is an important constituent. The silica comprising the sand and the cement is usually added to the silica which occurs combined in the aluminum silicates. There is no means of knowing what percentage of this silica may be considered as quartz and what percentage may be combined with the alumina and water to form kaolinite. For this reason most clay analyses show a percentage of silica sufficiently high to combine with all of the available alumina as kaolinite regardless of the fact that a certain percentage of this alumina may have existed in the clay as an aluminum hydrate.

Fortunately many of the later reports have incorporated with the ultimate analysis a "rational" analysis in which the percentages of clay substance, quartz and impurities have been determined. The clay substance contains the hydrous aluminum silicates. The impurities include fragments of undecomposed primary minerals, chiefly feldspars. From such an analysis the percentage of silica occurring as sand was subtracted from the total percentage of silica making it possible to recalculate into kaolinite only that percentage of silica which actually occurred in the combined form.

There seems to be a growing and well-founded tendency no longer to regard clay as composed of the minerals kaolinite and quartz but to regard it as a more or less indefinite mixture of a series of related secondary hydrous aluminum silicates at least some of which are claimed by H. Stremme[1] to be merely mixtures of colloidal silica and colloidal alumina. Others affirm that they are definite compounds. In order to recalculate the chemical analysis of a clay into mineral composition, the "clay" of mechanical analysis must be assigned some definite chemical composition. Ries says[2] that washed kaolins approach closely to the

[1] H. Stremme, *Centralbl. Min. u. Pol.*, 1911, p. 197.
[2] H. Ries, "Clays," p. 201.

composition of kaolinite. Rolfe[1] states that kaolinite which is generally recognized in clay analyses as the clay base, closely approximates the average composition of this group of hydrous aluminum silicates. In a study of Iowa clays, Beyer and Williams[2] assume the presence of pholerite ($2Al_2O_3 \cdot 3SiO_2 \cdot 4H_2O$) to explain the presence of any excess alumina. The possibility of the presence of pholerite, allophane ($Al_2O_3 \cdot SiO_2 \cdot 5H_2O$), or some similar silicate which contains a higher alumina-silica ratio than does kaolinite, must be regarded as a valid explanation for slight excesses of alumina if such compounds can be proven definitely to exist. On the other hand may be mentioned comolite ($2Al_2O_3 \cdot 9SiO_2 \cdot 6H_2O$) and montmorillonite ($Al_2O_3 \cdot 4SiO_2 \cdot H_2O$), which show a decided excess in the percentage of silica relative to the alumina. A mixture of a series of compounds from these two groups would yield upon analysis a resultant composition quite like that of kaolinite. Hilgard[3] believes the minerals of the allophane group to be relatively rare in clays.

From the above facts it seems reasonable to assume kaolinite as a basis for recalculation.

Mineral recalculations in this investigation were made by means of the "mineralogical slide-rule"[4]—a circular computing diagram involving the logarithmic principle. Alumina, silica and water are combined in the proportions required for the composition of kaolinite. If this calculation uses up all of the alumina, leaving an excess of silica, there is obviously no aluminum hydrate in the clay. But if there remains some alumina in excess it may reasonably be attributed to one of the aluminum hydrates, diaspore, bauxite or gibbsite, depending upon the relative percentages of alumina and water excess. The alkalies and alkaline earths, which are usually present to a slight extent, are ignored. This calculation, simple and empirical as it appears, seems to be justifiable, as the alumina-silica ratio alone needs to be considered and the other constituents are important only

[1] C. W. Rolfe, Illinois State Geol. Surv., Vol. 9, p. 11.
[2] Beyer and Williams, Iowa Geol. Surv., Vol. 14, p. 52.
[3] E. W. Hilgard, "Soils," p. 389.
[4] W. J. Mead, "Some Geological Short-Cuts," ECON. GEOL., Vol. 7, No. 2.

insofar as they affect this ratio. The bases which are usually present only to the extent of a few per cent. do not affect this ratio materially. It is not definitely known how they occur. They may be present in fragments of undecomposed feldspars or other silicates as the zeolites, or as oxides in some way absorbed or mechanically retained by the clay. But it is significant to note that in some primary minerals the alumina-silica ratio is identical with that of kaolinite, hence will not modify the relative percentages of alumina and silica upon recalculation. Most of the primary minerals show an excess of silica with reference to the alumina, as in orthoclase, in which the molecular ratio is 6 : 1. In calculating as kaolinite the alumina and silica contributed by these minerals a part of the excess alumina, should any exist, would be consumed in order to satisfy the four additional molecules of silica, thereby allowing no possibility for exaggerating the percentage of alumina in excess and strengthening to that extent the conviction that the clay considered does contain some aluminum hydrates. As Hilgard expresses it.[1]

"Since some of the alumina undoubtedly takes part in the formation of the zeolites the silica must to that extent be withdrawn from the estimate made for kaolinite. While it is impossible to make any definite numerical allowance for this fact it clearly tends in many cases to increase materially the amount of alumina that must be assigned to the hydrate condition."

It is impractical by this method, of course, to differentiate accurately between diaspore, bauxite and gibbsite, as most of the undecomposed minerals in the clay contribute alumina and silica, but no water, to the analysis. When kaolinite is calculated, water is withdrawn from the analysis to complete the kaolinite molecule. Consequently the actual amount of water is not available in the final calculation of the aluminum hydrate.

RESULTS OF RECALCULATION.

The total number of clay analyses examined during the course of the investigation was 2,310. Only those clays described as carrying no bauxite were considered. In only 244 of the total number of analyses had the free and combined silica been sepa-

[1] E. W. Hilgard, "Soils," p. 391.

rated. By recalculation it was found that in 180 analyses there was an excess of alumina. It seems significant that of these 244 analyses there were 108 analyses—44.3 per cent.—which yielded an excess of alumina. If this percentage holds generally, excess alumina would have been found in 44.3 per cent. of the total number of clays examined, had the percentage of silica present as quartz been determined in each case. In 72 analyses in which free and combined silica had not been separated, there was sufficient alumina present to combine with all of the silica as kaolinite and still show enough in excess to represent conspicuous percentages of aluminum hydrate.

Clay analyses from forty states were examined. In Alabama, Georgia, Arkansas, New Mexico and Tennessee the aluminum hydrates are known at present to exist in deposits of commercial value. The states in which the aluminum hydrates were found to exist in clays are listed below. Undoubtedly a still more extensive search through the clay analyses from many of these states would reveal analyses which show still higher percentages of bauxite.

States.	Per Cent. of Bauxite.	Number of Analyses
Alabama	9.9	1
Arkansas	2.33	1
California	43.5	1
Florida	.8	2
Georgia	11.8	36
Indiana	6.6	7
Illinois	7.65	1
Iowa	31.7	12
Kentucky	13	6
Maryland	.54	1
Massachusetts	2.2	1
Mississippi	17.6	4
Missouri	11.9	6
New Jersey	7.35	16
New York	32.2	1
North Carolina	24.8	44
Ohio	4.37	6
Pennsylvania	9.4	12
Texas	1.18	1
Washington	22.8	2
West Virginia	7.2	1

The above analyses are from the following sources:

Alabama—Prof. Paper, U. S. Geol. Survey, No. 11, p. 70.
Arkansas—Univ. of the State of N. Y., Museum Bull. 35, p. 860.
California—Univ. of the State of N. Y., Museum Bull. 35, p. 866.
Florida—Prof. Paper, U. S. Geol. Survey, No. 11, pp. 39, 83.
Georgia—Prof. Paper, U. S. Geol. Survey, No. 11, pp. 87, 88.
Geol. Surv. Georgia, Bull. 7A, pp. 108, 112.
Geol. Surv. Georgia, pp. 126, 133, 139, 165, 169, 176, 180, 188, 193, 205, 216, 221, 226, 257, 267, 270, 273, 274, 294, 306, 311, 313, 327, 348, 412.
Indiana—Prof. Paper, U. S. Geol. Survey, No. 11, pp. 105, 106.
Univ. of the State of N. Y., Museum Bull. 35, pp. 862, 866, 900.
Illinois Geol. Surv., Vol. 9, p. 13.
Illinois—Trans. Wis. Acad., Vol. 3, p. 28.
Iowa—Iowa Geol. Surv., Bull. 14, pp. 393, 398, 431, 438, 445, 471, 473, 489.
Kentucky—Prof. Paper, U. S. Geol. Survey, No. 11, p. 122.
Univ. of the State of N. Y., Museum Bull. 35, pp. 866, 868.
Maryland—Prof. Paper, U. S. Geol. Survey, No. 11, p. 145.
Massachusetts—Prof. Paper, U. S. Geol. Survey, No. 11, p. 150.
Mississippi—Miss. Geol. Surv., Vol. 2, pp. 44, 156.
Missouri—Ill. Geol. Surv., Vol. 9, p. 13.
Univ. of the State of N. Y., Museum Bull. 35, pp. 868, 870, 872.
New Jersey—Prof. Paper, U. S. Geol. Survey, No. 11, pp. 40, 164, 165.
Univ. of the State of N. Y., Museum Bull. 35, p. 880.
New York—Univ. of the State of N. Y. Museum Bull. 35; p. 890.
North Carolina—Prof. Paper, U. S. Geol. Survey, No. 11, pp. 39, 180, 183, 184, 185.
Ohio—Prof. Paper, U. S. Geol. Survey, No. 11, p. 205.
Ohio Geol. Surv., Vol. 7, p. 221.
Univ. of the State of N. Y., Museum Bull. 35, p. 872.
Pennsylvania—Univ. of the State of N. Y., Museum Bull. 35, pp. 874, 876.
Prof. Paper, U. S. Geol. Survey, No. 11, pp. 214, 220, 230.
Texas—Ill. Geol. Surv., Vol. 9, p. 13.
Washington—Ann. Rept., Wash. Geol. Surv., 1901, p. 175.
West Virginia—Prof. Paper, U. S. Geol. Survey, No. 11, p. 257.

It is clear from this table that aluminum hydrates occur in clays of temperate climates. They are not confined to tropical climates. None, however, were found in glacial clays.

A graphical presentation of this data is given on the accom-

panying plates. Fig. 41 is a triangular diagram on which the line drawn from the point representing 100 per cent. water through "kaolinite" divides the triangle according to the alumina-silica ratio characteristic of kaolinite. Siliceous clays fall below

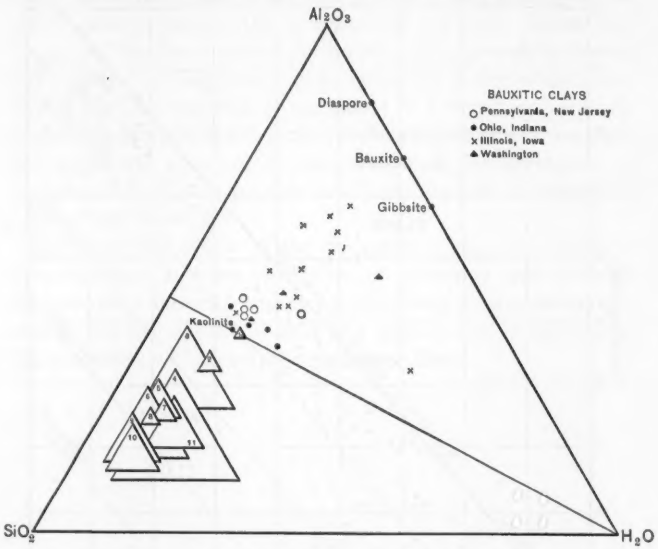

FIG. 41. Triangular diagram showing chemical compositions of Siliceous and Bauxitic Clays. Typical Clays (Siliceous): 1, Kaolin; 2, Flint Clay; 3, Stoneware Clay; 4, Slip Clay; 5, Paving Brick Clay; 6, Adobe; 7, Fire Clay; 8, Terra Cotta Clay; 9, Glacial Clay; 10, Loess; 11, Brick Clay.

this line. Clays falling above the line consist of a mixture of kaolinite, aluminum hydrates and quartz. The alumina-silica ratio has been maintained in plotting each analysis. Analyses of ten typical clays[1] are shown. They all fall below the kaolinite line. Above the line are plotted analyses of twenty-four clays from northern states showing varying percentages of alu-

[1] Illinois State Geol. Survey, Bull. No. 9, pp. 13 and 14.

minum hydrates. In Fig. 42 are plotted 150 clays from the United States based upon the alumina-silica ratio. These clays contain aluminum hydrates, recalculated as bauxite, the percent-

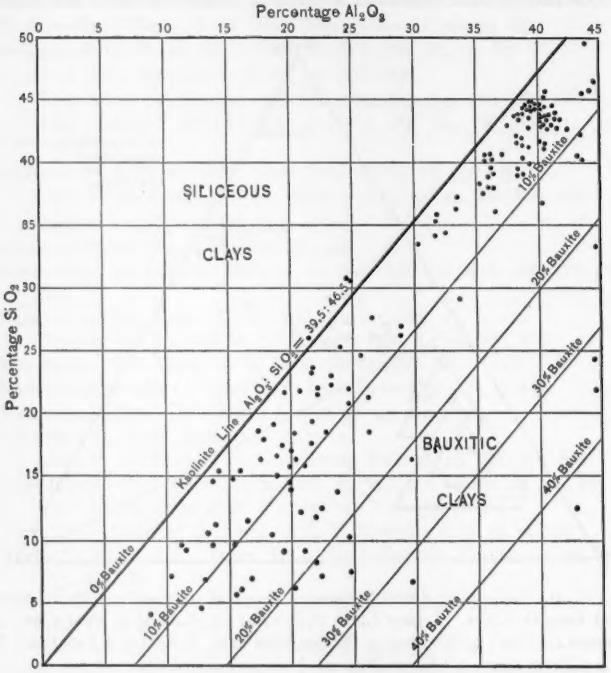

FIG. 42. Diagram showing Percentages of Bauxite in 150 Clays.

age of which is automatically registered in the triangle to the right of the "kaolinite" line.

CONCLUSION.

Assuming the validity of the above method of mineral recalculation the occurrence of aluminum hydrates is more or less

widespread in the clays of the United States. There seems to be nothing inherent in the conditions of weathering which admits of the possibility of the formation of aluminum hydrates only in tropical countries. Under certain conditions in temperate climates kaolinization may be the final process in rock decomposition. Under other conditions this is apparently not true. Indeed it is recognized that lateritization is a more common process in tropical climates than in temperate. In so far as this is true climatic conditions must be regarded as one factor in a consideration of the causes which determine which of the two processes will take place, but apparently does not exclusively control the alteration. A consideration of other possible conditions does not lie within the scope of this investigation.

More detailed study on the comparative rate and extent of decomposition in these two types of alteration will doubtless disclose many factors whose importance have hitherto been minimized, and will eventually lead to a quantitative comparison of the conditions which control or influence them.

TOURMALINE BEARING GOLD QUARTZ VEINS OF THE MICHIPICOTEN DISTRICT, ONTARIO.[1]

A. H. MEANS.

INTRODUCTION.

A suite of specimens collected by Professor W. O. Crosby from the gold bearing veins of the Michipicoten District, Ontario, was recently examined in the geological laboratory of the Massachusetts Institute of Technology, and this investigation revealed certain features which have a bearing on the genesis of these deposits. Although the locality was not visited it was thought worth while to present the conclusions arrived at from the laboratory study. The field relations are in fact carefully explained in a valuable paper by Professor W. O. Crosby[2] which also contains a review of the opinions expressed by Professor A. P. Coleman[3] on the gold quartz veins of Ontario.

The gold quartz veins of the Michipicoten District of Central Algoma, Ontario, are in the vicinity of Lake Wawa, a narrow sheet of water about 6 miles in length, situated about 6 miles northeast of Michipicoten Bay on Lake Superior, with which it is connected by Wawa Creek. Wawa City is located at the lower end of the lake. The district is situated in a large area of Lower Huronian schists,[4] into which Post Huronian granites and other acidic and basic igneous rocks have been intruded. The age of these intrusives is considered as Keweenawan.

A mile or two to the north of Wawa Lake is a small area of the iron bearing Helen formation, also Lower Huronian, in

[1] For advice and criticism I am indebted to Professor W. Lindgren; for the photographs, to the skill of Professor C. R. Hayward.

[2] "Origin and Relations of the Auriferous Veins of Algoma (Western Ontario)," *Technology Quarterly*, Vol. 15, 1902.

[3] Ontario Bureau of Mines Reports, Nos. 4, 5, 6, 1894–1896 incl.

[4] Map of Michipicoten Iron Ranges west of Magpie River, 14th Report Ontario Bureau of Mines, 1905.

which the Helen iron mine is located. The region, as described by Professor Crosby, is topographically rugged, heavily forested and contains many swampy depressions. Prospecting is difficult and geological work practically impossible save along the lake shores and in the mines themselves. The country rock of the area, as stated by Crosby, is the Huronian series and consists of a complex development of quartzites, slates, etc. These sedimentaries are cut by an igneous complex of acid and basic types, consisting for the most part of granites, felsites, diorites and gabbros. The felsites are in part altered to sericite schists, the diorites and gabbros in part to chlorite schists. The igneous rocks are thought by Crosby to be intruded at several intervals though not much time elapsed between the successive intrusions, all being differentiates of one parent magma. The granites are the younger and on their common boundaries with the diorites penetrate and even seem to grade into the latter rocks.

Veins in general are divided by Crosby into two classes, which he calls endogenous and exogenous respectively. The former class of veins form in preexisting open fissures while the latter made room for themselves and grew like a root, the material being derived from the adjoining rock by lateral secretion.[1] The veins of the area which are mainly contained in the intrusive rocks are divided into two classes: (1) branching gash veins and (2) non-branching sheeted or lenticular veins. Crosby holds that both types of veins are exogenous in origin, *i. e.*, formed by lateral secretion, and that ascending solutions have played no important part in their formation. In brief Professor Crosby bases his statement that the veins were formed by lateral secretion upon the facts that the veins are massive, devoid of true comb-structure and vugs and that isolated inclusions of wall rock occur in the vein material. Coleman,[2] in general, questions the sufficiency of the lateral secretion theory for both types of veins and holds that they were originally open fissures through which solutions circulated and deposited the vein material.

[1] Crosby, W. O., *Technology Quarterly*, Vol. 15, 1902, p. 178.

[2] Coleman, A. P., Ontario Bureau of Mines Rept., Nos. 4, 5, 6, 1894–1896 incl.

COUNTRY ROCK.

The country rock of the veins as shown by Professor Crosby's collection will first be considered. Only intrusive rocks or schists derived from them are represented. As stated these are Post Huronian, probably of Keweenawan age, and have been intruded through the Lower Huronian sediments which cover the district. The intrusives consist of granite and diorites with occasionally local variations in texture. The type granite of the region, to which the other rocks of the same class correspond within close limits, can be described as follows. In the hand specimen the rock is seen to be of a general gray color and medium texture, the latter at times approaching a porphyritic habit. At times a schistose structure is apparent and signs of shearing are evident though in the majority of cases the rock is even granular, holocrystalline and free from indications of dynamic action. The essential minerals are quartz, feldspar and biotite, the relative proportions of the three toward one another varying somewhat in different cases. Pyrrhotite and pyrite are present in most cases as accessory constituents.

In thin section the feldspar is seen to be predominately orthoclase in rudely tabular crystals and as irregular grains as well. In some cases a relatively small amount of andesine accompanies the orthoclase, and generally is tabular in outline and shows both albite and carlsbad twinning. Albite is also seen to some extent and appears to be more abundant than the andesine. The feldspars are for the most part greatly altered to sericite. Biotite occurs scattered in small crystals through the slide and is locally bunched in irregular aggregates. These aggregates are often surrounded by muscovite which seems to be an alteration product of the biotite. In some extreme cases the change has gone so far that all that is left of the biotite is a small spot of the mineral in the midst of the muscovite. Chlorite is also present to a limited extent as an alteration product of the biotite. In many cases pyrrhotite is seen to be intimately associated with the biotite and is included by the latter. Black iron ore is also

included in like manner. Some titanite and apatite are also present. The quartz is both primary and secondary. The primary quartz occurs in rather large grains of irregular rounded outline, the edges of the grains often having a ragged appearance. Secondary quartz and a little calcite (some of the latter derived from alteration of soda-lime feldspar) were deposited from infiltrating solutions at about the same time. In some instances the quartz appears to be the older and in others the calcite, so that it may be assumed that the deposition of both occurred at the same time. Both are present as interstitial grains of small size and rounded outline and in places are very intimately associated. From the above data it is permissible to conclude that the granites of the region are alkali rich, considerably altered and have been subjected to the action of siliceous and carbonate solutions.

MINERAL COMPOSITION OF THE DIORITES.

Although fairly uniform throughout the district there is more local variation in the component minerals of the diorites than was true in those of the granites. The diorites for the most part contain some quartz, though some now greatly altered specimens appear to have been typical diorites The type rock is even granular and of medium texture, black and white mottled with the black minerals predominating. The principal mineral is hornblende which occurs in slender prisms 1–2 mm. in length and in compact bunches. Quartz and feldspar come next, the latter being not determinable in the hand specimen. The quartz is but sparingly present and only at times visible megascopically. Pyrrhotite is usually present and in some cases is markedly so, it often being seen in irregular grains up to 1 mm. in diameter. In the thin section the rock is seen to have been considerably altered. The feldspar seems to be an oligoclase or oligoclase-andesine but is altered to epidote. In places the primary feldspar crystals are masses of fine crystals of epidote. The feldspars also usually contain some fine muscovite. A little orthoclase is present but is greatly altered to sericite. The hornblende is rather fresh, shows strong pleochroism, yellow to grayish blue, is optically positive,

has a maximum extinction angle of 12° and is idiomorphic toward the feldspar. Pyrrhotite and black iron ore are intimately associated with the hornblende and are included by the latter. Quartz, both primary and secondary, is usually present, and though in most cases it is easy to distinguish between them, it is not always possible to do so. The primary quartz occurs as a rule in large irregular grains with frayed edges. In many cases it forms a granophyric intergrowth with the feldspar, an example being shown in the accompanying photomicrograph (Fig. 43).

FIG. 43. Quartz diorite from Mackey's Point. Shows granophyric intergrowth of quartz and feldspar. Nicols crossed. × 25.

Biotite, which was the essential ferro-magnesian mineral of the granites, is only sparingly present. It is greatly altered to chlorite, the latter being intergrown with secondary quartz in many cases. Apatite is abundantly present and large hexagonal crystals are frequently seen. Secondary quartz and calcite appear to have been introduced simultaneously.

The alteration of the rock consists of two phases: (1) The general recrystallization due to common hydrometamorphism, and (2) the infiltration of quartz and calcite in veinlets. The general type of granite and general type of diorite of the region are clearly related. The predominating feldspar of the granite is orthoclase with some albite and oligoclase-andesine present in subordinate amount while that of the diorite is oligoclase or

FIG. 44. Quartz diorite from Mackey's Point, showing pyrrhotite with hornblende. Nicols uncrossed. × 25.

oligoclase-andesine. Both rocks contain biotite, a principal constituent in the granites and an accessory in the diorites. Pyrrhotite and black iron ore are present in both, and both contain secondary quartz and calcite in about the same amount. Apatite is present in both rocks, it being more abundant in the diorites. It is well possible that both diorites and granites are differentiates of a parent magma.

VEINS AND WALL ROCK.

The veins themselves will next be considered. They are in general composed of quartz and a sideritic carbonate determined by Professor Crosby as ankerite. The scant sulphides consist of pyrite, pyrrhotite and chalcopyrite. There is also a little biotite and ilmenite, in some cases also tourmaline. Gold occurs native in deep yellow irregular flakes and grains some of which are quite large.

The veins are small, at most a few feet wide, and consists predominatingly of massive, milk white to glassy quartz. This quartz is coarsely crystalline and composed of rather large, regular but allotriomorphic grains. The quartz contains few minerals other than occasional grains of pyrite, pyrrhotite, chalcopyrite and gold. The quartz from the Hornblende Mine contains small prisms of tourmaline.

Along the edges of small quartz seams a little of the ankeritic carbonate is often found and this carbonate spreads through the adjacent country rock. Some of the larger veins are lined by masses of the same ankerite which was evidently deposited earlier than the quartz for it sometimes borders against the quartz with crystallographic outlines. This coarse-grained carbonate in irregular but equidimensional grains contains in places a few flakes of biotite and chlorite, with grains of pyrrhotite and ilmenite.

The gold is present both in the middle of quartz grains and in the interstices between grains. When occurring in the latter manner it is usually accompanied by pyrite, pyrrhotite, and sometimes tourmaline. In one case, native gold is seen embedded in a matrix of tourmaline and muscovite with a little quartz.

The wall rocks from several prospects are represented in the collection. In one case biotite granite forms the wall rock but in general the dioritic rocks predominate. Most of these rocks contain much chlorite and some are converted to chloritic schists.

The rocks adjacent to the veins are not bleached but retain their dark color and crystalline structure. Thin slabs of black, highly altered schist are often enclosed in the quartz.

Microscopic examination has shown that tourmaline enters to

considerable extent in the country rock and this tourmalinization of the rock adjacent to the vein is the principal point which it is intended to bring out in this discussion.[1] The narrow bands of highly altered country rock embedded in quartz consist of a highly tourmalinized schist. One specimen from Mackey's Point on Lake Wawa shows this well.

The including quartz and ankerite are in this case entirely free

FIG. 45. Altered wall rock included as vein material, Hornblende Mine. Shows tourmaline crystals including quartz and calcite. Tourmaline occurs in matrix of fine muscovite and some quartz. Tourmaline also cuts calcite crystal. Nicols uncrossed. × 25.

from tourmaline. The black bands of schist when examined in the thin section showed fine needles of tourmaline set in a matrix of finely crystalline muscovite. A little chlorite is seen here and there in the tourmaline and muscovite aggregate. These broad

[1] The occurrence of tourmaline in the quartz was mentioned by Professor Crosby from one of the prospects, called the Hornblende Mine.

streaks or inclusions of muscovite and tourmaline beyond doubt represent fragments of very highly altered country rock. This country rock being in the neighborhood of the fissure was acted upon by the mineralizers and was altered to its present extent. What was its original composition it is impossible to tell, but judging from other less altered types the rock was probably a diorite or a chlorite schist. The thin section also shows an instance where some carbonate is included in the muscovite and completely surrounded by it. This carbonate contains tourmaline and muscovite. From this it is seen that the carbonate of the country rock is older than that of the vein filling. When the vein filling was deposited these altered portions of country rock were mechanically included and became part of the vein proper. The gold which has just been mentioned as occurring in the tourmaline-muscovite matrix, therefore, occurs in the greatly altered country rock included by the vein, and must have been carried there by the mineralizers which deposited the tourmaline and muscovite. Another point of interest is the abundance of pyrrhotite occurring with the tourmaline compared to that found in other portions of the rock. With the pyrrhotite are often intergrown pyrite and to a less extent chalcopyrite.

At the Hornblende Mine two miles east of Lake Wawa the wall rocks are especially rich in tourmaline. The normal rock is a chloritic schist in all probability derived from a quartz diorite. A hand specimen shows a contact between the quartz of the vein itself and greatly altered country rock included in the vein.

The coarse grained massive quartz contains scattered needles of tourmaline, especially near angular inclusions of a dark granular material which undoubtedly represent inclusions of altered country rock. Under the microscope these dark areas are shown to consist of prisms of tourmaline embedded in muscovite, calcite and quartz, together with some pyrite, pyrrhotite and chalcopyrite (Fig. 46.) Some biotite is also present, occurring in the vicinity of the tourmaline. The calcite is later than the tourmaline in this case and contains inclusions of black iron ore as does the

tourmaline. The quartz present is earlier than both the calcite and the tourmaline; it contains a little ilmenite or magnetite. No gold was seen in the specimen. This rock is very similar to the occurrence at Mackey's Point just described. The tourmaline bearing material is greatly altered country rock which has been mineralized by emanations from the nearby fissure and here,

FIG. 46. Vein material from Mackey's Point. Tourmaline included by fine muscovitic groundmass. Nicols uncrossed. × 25.

as at Mackey's Point, mechanically included by the vein filling. This filling is composed of quartz and a sideritic carbonate, probably ankerite. The carbonate occurs along the contact between quartz and wall rock. Both quartz and carbonate contain small amounts of sulphides, pyrite, chalcopyrite, pyrrhotite, and of tourmaline. Free gold is seen in the quartz both in individual grains and in interstices beween grains. No gold was seen in the carbonate.

Three other specimens of the wall rock from the Hornblende Mine likewise contain tourmaline but are less altered and the original character of the rock is more clearly evident. In general the rocks are distinctly schistose, streaked darker and lighter green and some contain veinlets or little lenses of quartz. Alternating bands of quartz and calcite with darker chloritic streaks as well as small black prisms of tourmaline are visible with the magnifying glass.

Under the microscope the schists consist of alternate bands of chlorite and of quartz and calcite. The chlorite extends in rather

FIG. 47. Showing alteration of biotite to chlorite. Black is biotite, gray chlorite, center of slide tourmaline, high relief calcite. From Hornblende Mine. Nicols uncrossed. ×25.

broad bands across the slide and contains tourmaline in grains and prisms and is probably derived from hornblende and biotite. Fragments of the latter mineral are seen included by the former (Fig. 47). Of the original constituents of the rock primary

quartz is the only mineral remaining. It occurs in irregular grains of ragged outline. Calcite and secondary quartz are abundantly present and occur intimately associated in small shapeless grains. The tourmaline occurs principally in the chlorite and along the contact between the latter and the quartz and calcite. It is as a rule well crystallized in slender prisms which extend parallel to the direction of the schistosity of the rock.

FIG. 48. Tourmaline (center of picture) in chlorite showing how the former has made room for itself and pushed aside the chlorite. Black material pyrite, pyrrhotite and black iron ore. From Hornblende Mine. Nicols uncrossed. ×25.

In several instances the tourmaline has forced aside the chlorite in order to make room for itself during crystallization and is therefore a later mineral. This is distinctly shown by the manner in which direction of the schistosity has been changed in the immediate vicinity of the tourmaline crystals (see Fig. 48). A small amount of muscovite is present and is irregularly distrib-

uted. Pyrite, pyrrhotite and black iron ore are present in small but varying amounts and are intimately associated with tourmaline.

SUMMARY.

From the foregoing data it seems most probable that these veins have been formed in open fissures, the mineralizers and vein filling being supplied from below. The original country rock was first in part made schistose by dynamic metamorphism and later acted upon by solutions yielding carbonate and quartz, this action being general and not confined particularly to the vicinity of the veins. Pneumatolytic action then occurred in the vicinity of the veins, which served as channels for the mineralizers. The country rock in the vicinity was heavily tourmalinized, muscovite and biotite also being formed. These mineralizers diffused into the country rock on both sides of the vein and when crystallizing made room for themselves by solution of corresponding parts of the country rock. These same mineralizers also carried some gold as is shown by the intimate association of the gold and tourmaline. After this heavy mineralization in the vicinity of the veins the vein filling of quartz and ankerite was deposited. The quartz vein filling is the principal gold carrier, the metal occurring native and alone though in some instances it is intimately associated with pyrite and pyrrhotite, the latter minerals being greatly intergrown with one another and with chalcopyrite. The filling of the veins started shortly after the mineralization and before it had entirely ceased as is shown by the presence of small amounts of tourmaline in the vein quartz. The carbonate occurring with the quartz contains a sprinkling of sulphides and is probably but slightly older than the quartz.

According to the reports of the Ontario Bureau of Mines, this type of deposit is not unique in this region. The Lyle Mine on Dryweed Island is working quartz veins in a Keewatin schist, the vein materials being pyrite, tourmaline and a carbonate.[1]

[1] 5th Rept. Ont. Bur. Mines, 1895, p. 63.

Another occurrence is at the Keewatin Mine, Big Stone Bay, where quartz gash veins contain pyrite and tourmaline.[1]

In the case described in this paper the strong tourmalinization of the wall rocks is a noteworthy feature and indicates that the veins were deposited by ascending and very hot solutions probably derived from the intrusives injected into Huronian sediments.

[1] 4th Rept. Ont. Bur. Mines, 1894, pp. 68–69.

SOME GRAPHIC METHODS FOR THE SOLUTION OF GEOLOGIC PROBLEMS.

W. S. TANGIER SMITH.

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INTERSECTING PLANES.

The line of intersection of two planes, in contour projection, passes through the point of intersection of the main traces of the planes, and, in general, through the point of intersection of the contours of the two planes at any given level. The projection of the line of intersection may therefore be obtained by passing a line through the projected points of intersection of any two sets of contours of the two planes. If the main trace or any contour of one of two intersecting planes is parallel to a contour of the other plane, the line of intersection of the two planes must be parallel to these contours and to the reference plane.

Problem 28.—Given the dip and strike of each of two intersecting planes, to determine (1) *the dip angle of their line of intersection and the strike of the vertical plane through this line;* (2) *the angle formed in either plane by a horizontal line in that plane and the line of intersection of the two planes.*

One of the two planes may be a bed, vein, dike, or fault plane; the other may be an intersecting vein, dike or fault plane, or merely a constructional plane drawn for the purpose of obtaining a section. The problem is an important one, especially because,

[1] For Part I., see ECON. GEOL., Vol. IX., No. 1, pp. 36-77.

in one of its aspects, it is so frequently met in the construction of structure sections where the section line meets dipping beds or veins diagonally.

1. Let *ABCD* and *AEFG* (Fig. 49) be the projections of the two given planes. Produce the projected contours *CD* and *FG* till they intersect in *H* and draw *AH*. This is the projection of

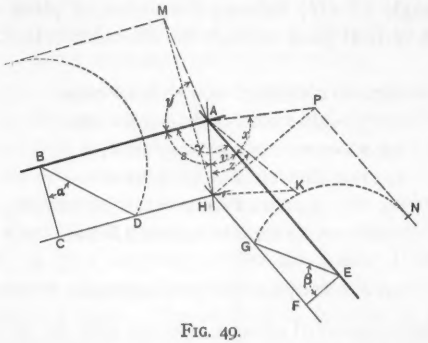


FIG. 49.

the line of intersection of the two planes, and the strike of the vertical plane passing through it. To determine the dip angle of the line of intersection, rotate the vertical plane containing it, into the reference plane, locate the point *K*, of which *H* is the projection, and draw *AK*. *KAH* is the required angle of dip.

2. Rotate the two projected planes, *ABCD* and *AEFG*, into the plane of projection and draw in the rotated planes the lines *AM* and *AP*, which are the lines of intersection in either plane corresponding to the projected line of intersection *AH* (Problem 3). *BAM* and *EAP* are the required angles made in the respective planes by a horizontal line, and the line of intersection of the two planes.

If the dip of plane $ABCD = \alpha$,
the dip of plane $AEFG = \beta$,
the angle (BAE) between the strikes of the two planes $= \gamma$,
the angle (EAP) between strike and intersection line in plane $AEFG = x$,

the angle (BAM) between strike and intersection line in plane $ABCD = y$,

the angle of dip (HAK) of the intersection line of the two planes $= z$,

the angle (BAH) between the strikes of plane $ABCD$ and the vertical plane through the intersection line $= s$,

the angle (EAH) between the strikes of plane $AEFG$ and the vertical plane through the intersection line $= v$,

Then,

$$\cot x = \cot\alpha \sin\beta \csc\gamma + \cos\beta \cot\gamma,$$
$$\cot y = \sin\alpha \cot\beta \csc\gamma + \cos\alpha \cot\gamma,$$
$$\sin z = \sin x \sin\beta = \sin y \sin\alpha,$$
$$\tan z = \sin v \tan\beta = \sin s \tan\alpha,$$
$$= \tan x \sin\beta \cos v = \tan y \sin\alpha \cos s,$$
$$\cot v = \cot x \sec\beta = \cot\alpha \tan\beta \csc\gamma + \cot\gamma,$$
$$s = \gamma - v,$$
$$\cot s = \cot y \sec\alpha = \tan\alpha \cot\beta \csc\gamma + \cot\gamma.$$

The determination of either s or v will give the strike, AH, of the vertical plane through the line of intersection of the two given planes.

If one of the two intersecting planes ($ABCD$ and AE, Fig. 50) is vertical (AE), as is the case in constructing a vertical

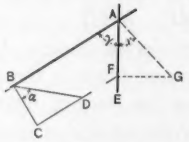


FIG. 50.

section, the angle of dip of the line of intersection of the two planes coincides with the angle formed in the vertical plane by this line of intersection and a horizontal line of the plane—*i. e.*, $x = z$.

The determination of the angle of dip of the line of intersection—usually the only angle required—is made by rotating this

plane (main trace AF) into the reference plane, determining the point G, corresponding to the projection F, and drawing AG. FAG is the required angle.

Since β, here, equals 90°, the first equation of the list given above becomes

$$\tan x = \tan \alpha \sin \gamma.$$

THE INTERSECTION OF A PLANE WITH AN IRREGULAR SURFACE, BOTH REPRESENTED BY CONTOURS.

Problem 29.—Given an irregular surface represented by contours, and the dip and strike of a plane (bed, fault plane, vein, etc.) with outcrops at a given point on this surface, to draw the outcrop or line of intersection of the two surfaces.

This is a problem not infrequently met by the geologist, and its solution furnishes a means of mapping an outcrop where it is concealed, as on a detritus-covered hill-slope. It is also of value in accurate plotting in complex topography, even where the exposures are good. The method of solution is to obtain points of intersection between the contours representing the irregular surface and the corresponding contours of the plane, and to connect these points by a continuous line.

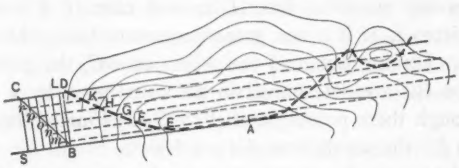


FIG. 51.

In Fig. 51, a point at which the given plane outcrops is shown at A. The strike at this point is AB, which becomes the main trace of the plane if the reference plane is assumed to pass through the point A. The dip of the plane is shown in the dip triangle at B, and the contours of the plane corresponding in altitude and vertical interval to those of the irregular surface are

indicated by the series of lines in the dip triangle parallel to *AB*. If *A* is not a full contour interval above the contour at *E*, then the first interval between *B* and *D* in the series of parallels must be made correspondingly less than the succeeding full contour intervals. By producing these parallel lines till they intersect the surface contours of corresponding altitude, the series of points, *E, F, G, H, K,* is obtained, and a line joining these points gives the outcrop.

The scale of the map or the regularity of the surface may be such that it is not necessary to construct contours for the plane corresponding to every surface contour, but a greater interval may be taken, the exact interval selected depending on conditions in the particular case.

To draw the contours of the plane parallel to *AB*, it is first necessary to obtain on *DC* of the dip triangle—or on *BS*—a series of points corresponding to the depth of the contours at *E, F, G,* etc., below the point *A*, the distances being determined in accordance with the scale of the map (see table, page 144). The distance *DL* is equal to the vertical distance below *A* of the contour at *E*, and the succeeding points are at distances corresponding to the distance between the contours used. These contour intervals are preferably measured from *D* in each case, if *A* is on a contour, or from *L*, if it is not, greater accuracy being obtainable in this way. Having obtained the points on *DC*, the points *m, n, o, p, r,* on *BC* are determined in the usual way, by a series of lines through these points parallel to *DB*. Finally through the points on *BC* the parallels to *AB* are drawn.

Instead of a graphic determination, the calculation of the distance between the parallels to *AB* may be made from the following equation:

Projected horizontal contour interval = actual vertical contour interval expressed in inches × cot angle of dip of plane × scale of map.

Calculation is especially preferable where the angle of dip is low, on account of the inaccuracies liable to result from the small angle between *DB* and *BC* and the relatively small contour interval on *DC*.

Problem 30.—Conversely, given the outcrop of a fault or other plane on a contour map of an irregular surface, to determine the dip and strike of the plane.

The determination of the strike in this problem depends on the fact that a plane never intersects the same contour of an uneven surface twice except in the line of strike of the plane. Therefore, to determine the strike of the given plane, first find on the map some contour which is crossed at least twice by the outcrop of the plane, as at *A* and *B*, Fig. 52, and connect these

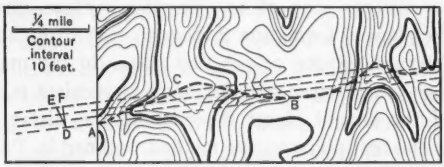


FIG. 52.

points of intersection by a straight line. This line, *AB*, becomes the main trace of the plane, whose angle of dip or dip triangle may then be obtained by drawing a line parallel to *AB*, through the point of intersection of the outcrop with some other contour which lies at a sufficient vertical interval below the main trace, as *C*. At some convenient point, as *D*, a perpendicular, *DF*, should be drawn between these two parallels, and the distance *EF* laid off to correspond to the vertical interval between *B* and *C*. Drawing *ED* completes the dip triangle.

From the above it will be seen that this problem is essentially an application of Problem 7. In solving the problem, it is not, however, necessary that two of the points used shall be at the same level and therefore in the line of strike. This merely serves to simplify the solution. The three points, *A*, *B*, and *C*, may be any three points along the line of outcrop, not in a straight line, and from these the dip and strike may be determined by the methods of Problem 7. In using either method of solution it is of course assumed that the general dip and strike are practically constant throughout the area involved in the problem.

Where the angle of dip is low (9½° in Fig. 52), and especially where the greatest available vertical interval is small (60 feet in Fig. 52), the dip may in general be more accurately determined by calculation than by graphic methods. The cotangent of the angle of dip equals the horizontal contour interval (*DF*), determined in feet as closely as possible, divided by the vertical contour interval (*EF*), expressed in feet.

If instead of a single plane, the outcrops of two parallel planes —for example, the two boundary planes of a formation—are given on a contour map of an irregular surface, the distance between the planes (formation thickness) may often be obtained by first determining one of the two planes in the manner just described, and then, after selecting some convenient point on the outcrop of the second plane, determining the distance of this point from the first plane by the method outlined in Problem 20.

It may readily be seen from Fig. 52, that, if the map is well made and the geological plotting carefully done, the limits of error in the determination of the strike of the plane whose outcrop is shown are not great; whereas there is a much greater possibility of error in the determination of dip. This is partly on account of the difference in the methods of constructing the vertical and the horizontal elements of both topographic and geologic maps, which admit, on the whole, of a much higher degree of accuracy in the horizontal element; and partly on account of the difference in the number and kind of measurements required in the determination of dip as compared with those involved in the determination of strike, and the relative degree of accuracy obtainable in them. In spite of all this, the determination of the general angle of dip by the method given here is often more accurate than that based only on scattered field readings.

If the plane intersecting the irregular surface (in Problem 29) is horizontal, the line of intersection, or outcrop, will of course correspond to one of the contours of the irregular surface, or will lie between two of these contours. If, on the other hand, the intersecting plane is vertical, the projection of its outcrop will be a straight line. This line coincides with the trace of the ver-

tical plane itself in the reference plane; and if this vertical plane be revolved about its trace into the reference plane, a vertical section of the irregular surface and of any other features intersected by the plane will be obtained.

The Construction of a Geologic Cross Section (Structure Section).

The paper used in making structure sections may be either unruled or ruled in one direction, or in two directions at right angles. When the horizontal scale of the section is the same as that of the map from which it is made, the vertical rulings are of little value, except, perhaps, to make it a little easier to adjust the location of points horizontally, Nor are the horizontal rulings necessary, although desirable where they are accurate, as serving to simplify the measurements of vertical distances. On account of the unequal spacing of much of the cross-section paper on the market, however, more accurate sections may often be made on unruled paper. The distance between the horizontal rulings of some of the paper used for making sections is adjusted to common map scales, and represents a given number of feet; for example, the distance between successive lines may represent a vertical interval of five hundred feet, on a scale of one mile to the inch, or two hundred and fifty feet, on a scale of two miles to the inch. This greatly reduces the work of projecting points in their vertical relationships. If such paper is not at hand, paper ruled in inches and tenths, or in centimeters and fractional parts, may be used. In this case a table should be prepared showing in terms of decimal parts of an inch or centimeter the value of any given number of feet in accordance with the vertical scale adopted.

Generally speaking, the vertical scale should always be the same as the horizontal scale of the section. There may be cases in which, for some special purpose, it is advantageous to make the vertical greater than the horizontal scale used; but the exaggeration is always misleading, and under ordinary circumstances it is neither necessary nor desirable.

If the scale of the map is one inch to the mile ($\frac{1}{63,360}$), one actual foot equals $\frac{1}{5,280}$ (.0001893) of an inch on the map. If the scale is $\frac{1}{62,500}$, one actual foot equals .000192 inch on the map; while a scale of $\frac{1}{45,000}$ gives for one actual foot a value of .00026 on the map. From these figures the following table has been constructed.

TABLE FOR DETERMINING DISTANCES IN STRUCTURE-SECTIONS.

Actual Feet.	Corresponding Measurements on Structure Section in Inches.		
	Scale 1:63,360.	Scale 1:62,500.	Scale 1:45,000.
10	.00189	.00192	.00266
20	.00379	.00384	.00533
30	.00568	.00576	.00800
40	.00758	.00768	.01066
50	.00947	.00960	.01333
60	.01136	.01152	.01600
70	.01326	.01344	.01866
80	.01515	.01536	.02133
90	.01705	.01728	.02400
100	.01893	.01920	.02666

In addition, ten actual feet equal .01 inch when the scale is 1:12,000 and .012 inch when the scale is 1:10,000. These scales need no tabulation.

While some of the values given above are too small for practical use, and some have been determined beyond necessary limits, they may serve as the basis of determination for other usable values. The values for hundreds and thousands of feet may readily be obtained from the figures given here, by moving the decimal point the proper number of places to the right; and for maps of other commonly used scales it is only necessary to multiply or divide by the appropriate factor. For example, multiplying the figures of the second column by four gives the corresponding values for a scale of four inches to the mile; or dividing those of the third column by two, gives the values for a scale of 1:125,000. Thus, from the figures given, values for a point at any elevation and for any ordinary scale may be obtained. Such values should be determined to the third decimal place, since with a good scale or accurately spaced parallel lines, and a fine-pointed pencil, points may easily be located to within a hundredth of an inch.

In constructing the cross section, a fine straight line should first be drawn on the map where the section is desired, and if the section is to have the same horizontal scale as the map, the latter may then be fastened on a drawing board so that the line of the section may be in parallel adjustment to the edge of a T-square. Next a piece of cross-section paper (if this is used), long and wide enough to contain the whole section, should be cut and fastened over the map, so that its horizontal lines are parallel to the line of the section, and its upper edge is a trifle below this line.

A base-level or reference plane from which to measure vertical distances should then be selected—usually sea level for sections in areas of moderate elevation, but preferably some nearer level at high altitudes. In the latter case this reference plane is generally located at some convenient level below the lowest point of the section, an elevation of some even hundreds or thousands of feet being desirable to simplify the calculations. When section paper is used, one of its horizontal lines is selected for the trace of this level, conveniently placed with reference to what will probably be the highest and lowest points of the completed section (including the geology), and is marked at one edge or the other of the paper with its elevation. If unruled paper is used, a fine pencil line is drawn for the base line, at some convenient point, and parallel to the section line of the map.

Next, a series of salient points is picked out on the map, along the line of the section, and these are carefully located on the section paper in succession, as they are selected. These points should include (1) the intersections of the section line with important contours; (2) all points where there is a reversal of slope, as at the summits of elevations and the bottoms of depressions; (3) the intersections of the section line with any other important features, as, for example, fault traces or geologic formation boundaries. The important contour intersections are those at which the slope changes. So long as the grade remains uniform along the line of the section, as indicated by the equal spacing of the contours, it is not necessary to use any except the bounding contours of that particular slope. If, however, the

horizontal distance covered by such a uniform slope is relatively great, one or more intermediate contour intersections may be used in order to facilitate the drawing of the final profile. Even where the contours are unequally spaced it is not always necessary to use them all, especially where the grade is changing uniformly. The judgment of the individual must decide what points will really be of assistance in constructing the final profile, and what may as well be omitted.

In plotting on the section paper the points selected along the section line, a T-square and a triangle may be used, the edge of the square being parallel to the horizontal lines or the base line of the section paper, and the triangle sliding along the upper edge of the square till its vertical side is in contact with the selected point on the section line. This vertical edge locates the point horizontally on the section paper, its vertical location being determined by its altitude above the base level. If the spacing of the horizontal lines of the paper is adjusted to the scale of the map, the point may be plotted directly; or if the spacing is in inches and tenths, the vertical distance of the point above the base line must first be determined from the table already referred to, after which the point may be located by the spacing of the paper, determining the subdivisions of the tenths with the aid of a lens if necessary. If the paper is without rulings except for the base line, a fine line should first be drawn along the edge of the triangle, and then the point located on this line at the proper interval above the base line, by means of a good scale marked with suitable subdivisions—*e. g.*, fiftieths of an inch. When the position of the point has been determined, both horizontally and vertically, it should be marked with a fine-pointed pencil.

When all the salient surface points have been located, they should be connected by a profile line lightly drawn in pencil. In drawing this line, constant reference should be made to the map for details and for the proper expression of surface features which cannot be obtained from the projected points alone. The line having been drawn in pencil is then ready for inking.

The filling in of the geology is too large a subject to be con-

sidered in detail here, and it is, besides, a process in which much must be left to the individual judgment. A single point only need be touched upon.

The intersections of the section line with important outcropping geologic structures should have been already located during the process of plotting surface points. These structures are now carried below the surface at their proper angles. In plotting a dipping formation, vein, dike or fault, unless the line of the section crosses the outcrop in the direction of the dip, the angle of dip in the section cannot, of course, be the true angle, but must be determined or calculated as in Problem 28, or it may be determined from the formation thickness and depth, by an adaptation of the method shown in Fig. 35. Sections are sometimes seen in which this point seems to have been entirely overlooked.

Structure sections may also, of course, be made directly in the field, by constructing the actual profile and plotting the geology along the line of the section, which may follow a straight course or a zigzag. By ignoring the measurement of horizontal distances in the field, and using only an aneroid barometer, supplemented where necessary by a hand level, for the vertical element, structure sections, in regions where the dip of the rocks does not exceed about five degrees, may be rapidly made in the field and later more accurately redrawn in the office. This method assumes that a good base map is available for the redrawing of the section, and also that numerous tie-points have been noted on the map and section during the construction of the latter, so that any point of the field section may readily be identified on the map.

This is, in outline, the method devised by Marius R. Campbell for the rapid field construction of geologic sections in areas of nearly horizontal rocks, which has proved so valuable in mapping where the strata consist of a monotonous series of similar rocks —*e. g.*, chiefly sandstones and shales—with no prominent and easily recognized beds persistent over any considerable area, distinctive fossils being rare and rock exposures poor. Considerable topographic relief, however, is a factor essential to the use of this method; but where all these conditions are met, beds or

horizons not ordinarily distinguishable may be identified with certainty by means of it. C. W. Hayes in his "Handbook for Field Geologists" (pp. 61–63) has given a brief account of the field practice essential to this rapid section work, though he has not treated the equally important office work. For this, reference must be made to Campbell's original article on the subject, the title of which is given in the list of references at the end of this paper.

THE INTERSECTION OF AN IRREGULAR SURFACE WITH A WARPED, FOLDED, OR IRREGULAR SURFACE.

To obtain the line of intersection of two uneven surfaces, as for example, the outcrop at the earth's surface of a folded formation (and especially at points where the outcrop is concealed), it is necessary that the two surfaces be represented by their projected contours, both maps being drawn to the same scale, and that the contour map of one of the surfaces be superposed on that of the other, either directly, by drawing it upon the latter, or by constructing it upon a transparent material—as tracing cloth—and using this as an oversheet on the other map. If, as is usually the case, one of the two surfaces in this problem is a topographic surface, and the other a bed or one of the surfaces bounding a formation, the contour map of the former may be used as a base for the construction of a contour map of the latter, the method of construction being that already given (page 64).

If two surfaces represented by contours intersect, their line of intersection must pass through the points of intersection of those contours of the two surfaces which are of like elevation. If, therefore, the contours representing the bed or formation surface are superposed on those representing the topographic surface, the intersections of contours of equal altitudes will give a series of scattered points along the line of outcrop of the bed or formation; and this outcrop may then be drawn by connecting the points by a continuous line. It not infrequently happens that in some parts of the map the drawing of the outcrop is doubtful on

account of an insufficient number of intersections between the corresponding contours of the two surfaces. In such places additional contours, both topographic and formational, may usually be interpolated without difficulty, and with sufficient accuracy, thus providing additional points of intersection along the line of outcrop.

The following will serve to illustrate the general method just described.

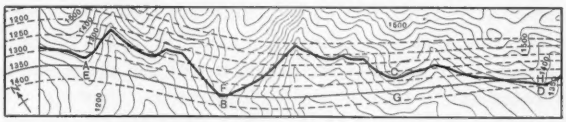


FIG. 53.

Let *A, B, C* and *D*, Fig. 53, be four localities at which a somewhat warped contact surface between two formations outcrops, the outcrop being concealed between these points. The elevations of the four points are, in the order given, 1,320 feet, 1,360 feet, 1,290 feet and 1,400 feet, and the dips at these points are 18°, 22°, 27° and 31° degrees respectively, all northeasterly.

To obtain the outcrop of the warped surface where it is concealed, the projected contours of that part of the surface adjacent to the outcrop must first be obtained. To construct these contours some one of them is first selected for projection, the level chosen often being that of one of the given points, for the sake of convenience. In this instance let the 1,350 ft. contour be that selected. The outcrop at *A* lies 30 feet vertically below this contour. From this vertical interval and the angle of dip at *A*, the horizontal distance from *A* to the projected contour is then obtained by means of the equation on page 140. With *A* as a center and the calculated horizontal distance as radius, a short arc is next drawn on the side of *A* opposite to that toward which the warped surface dips, since *A* is below the 1,350 ft. contour. In practice, sufficiently accurate results are commonly obtained by merely laying off the determined horizontal distance as nearly as possible in the line of dip, instead of constructing the circular

arc. This is the method which has been used here, and *E* is the resulting point.

In the same way the horizontal distances from *B*, *C* and *D* to the projected contour are obtained from the altitudes of the points and the dips of the warped surface at these localities; and the determined distances are laid off at *F*, *G* and *H*, respectively, *G* southwesterly from *C*, since the latter point is below the level of the projected contour, and *F* and *H* northeasterly from *B* and *D*, respectively, as the last named points are above this level.

E, *F*, *G* and *H* all lie on the projection of the 1,350 ft. contour, and this contour may now be drawn by joining the points by a smooth curve.

Next, at *E*, a series of points is laid off at right angles to the strike of the contour line just drawn, on either side of this line, the interval between the successive points being determined from the vertical interval selected for the contouring—50 feet in this instance—and the angle of dip at the point *A*, by means of the equation already used. In the same way series of points are laid off at *F*, *G* and *H*, the interval between successive points in each series being determined as for the series at *E*. Lines are then drawn joining corresponding points of the different series, the result being a series of curved lines which approach parallelism to the curved line *EFGH*. These are the required contours of the warped plane.

Where these curved contours of the warped plane intersect topographic contours of the same elevation, points on the outcrop of the warped surface are obtained. Where intermediate points are desired they may readily be obtained by interpolation, as already indicated. The resulting outcrop is shown in the figure.

This outcrop is, of course, only a close approximation, since the determination outlined here assumes that the dip of the warped surface above and below each of the points *A*, *B*, *C* and *D* remains essentially constant. In many instances the departure from the dips assumed will not be sufficient to appreciably affect the results. If, however, the dips vary rapidly above and below the given points of outcrop, the variation in dip should be ascer-

tained if possible, and the interval between the contours adjusted to these variations.

This method of plotting the outcrop where it is concealed may also be used when the formation surface is essentially a plane, only two points on the outcrop and one good determination of dip being necessary in this instance for the construction of the contours of the dipping plane.

OTHER PROBLEMS AND METHODS.

Among the problems which may be solved by the methods of contour projection, but not here considered, are those connected with faulting. An especially full treatment of the geometry of faults has already been given by Reid and Tolman (see list of references at the end of this article), and to their papers the reader must be referred. The methods and problems of the plane-table have not been considered directly in this paper, although many of the problems given here may be used in such work. Nor has map projection been touched upon, although a knowledge of its general principles is desirable for the geologist, since he is occasionally obliged to construct his own map. The essential principles of the polyconic projection of maps—the type of projection generally used for large-scale maps—are given in Bulletin No. 50 of the U. S. Geological Survey publications; while plane-table methods and problems, from the standpoint of the geologist, have been fully presented by Ransome and others in recent numbers of ECONOMIC GEOLOGY.

Other types of projection, while sometimes of value to the geologist, cannot be considered here, further than to mention one fact, which does not seem to be generally known, concerning isometric projection. That is, in making such projections it is not necessary, for most purposes, to use isometric proportions or an isometric scale. For, since length in the three essential directions in isometric projection is a mere matter of proportion, true length or any other convenient ratio may be used instead of the isometric.[1] This very much simplifies the use of this system of projection.

[1] See W. G. Smith, "Practical Descriptive Geometry," p. 199, 1912.

REFERENCES.

The following are some of the more important and readily accessible references relating to the graphic solution of geologic problems.

GENERAL.

C. W. HAYES. Handbook for Field Geologists, 2d ed., 1909.

JOSEPH W. ROE. Application of Descriptive Geometry to Mining Problems. *Trans. Am. Inst. Min. Eng.*, Vol. 41, 1911, pp. 512–533; republished as Chapter IX. of Farrell's Practical Field Geology, 1912.

Some general problems are also to be found under the two references which follow.

FAULTS.

H. F. REID. Geometry of Faults. Geol. Soc. America, Bull., Vol. 20, pp. 171–196, May, 1909. Also, Additional Note on the Geometry of Faults. Geol. Soc. America, Bull., Vol. 21, pp. 737–740, 1910.

C. F. TOLMAN, JR. Graphical Solution of Fault Problems, 1911.

STRUCTURE-SECTIONS AND STRUCTURE-CONTOURS.

MARIUS R. CAMPBELL. Rapid Section-Work in Horizontal Rocks. *Trans. Am. Inst. Min. Eng.*, Vol. XXVI., pp. 298–315, 1897.

A number of the U. S. Geological Survey Bulletins, also, outline methods for obtaining structure-contours, and several give, in addition, the method for constructing convergence maps; see especially Bulletins 318 and 454.

For two different applications of structure-contours, see:

Masontown-Uniontown Folio, Pennsylvania, U. S. Geol. Surv., Geol. Atlas of U. S., Folio No. 82, 1902.

Aladdin Folio, Wyoming-South Dakota-Montana, U. S. Geol. Surv., Geol. Atlas of U. S., Folio No. 128, 1905.

THE PLANE-TABLE.

D. B. WAINWRIGHT. A Plane-table Manual. Appendix No. 7, Report for 1905, U. S. Coast and Geodetic Survey, 1905.

F. L. RANSOME. The Plane-table in Detailed Geologic Mapping. ECON. GEOL., Vol. VII., No. 2, 1912, pp. 115–119.

C. H. WEGEMANN. Plane-table Methods as Adapted to Geologic Mapping. ECON. GEOL., Vol. VII., No. 7, 1912, pp. 621–637.

See also under Discussion, ECONOMIC GEOLOGY, Vol. VII., No. 5, 1912, pp. 502–506; and No. 8, 1912, pp. 778–783. Also a number of papers under Field and Office Methods in the Preparation of Geologic Reports, Vol. VIII., 1913.

MAP CONSTRUCTION.

R. S. WOODWARD. Formulas and Tables to Facilitate the Construction and Use of Maps. U. S. Geol. Surv., Bull. No. 50, 1889; also, Smithsonian Geographical Tables, 3d ed., Smithsonian Miscellaneous Collections, 854, 1906.

S. S. GANNETT. Geographic Tables and Formulas. Second Edition, U. S. Geol. Surv., Bull. No. 234, 1904.

Tables for a Polyconic Projection of Maps. Second Edition, U. S. Coast and Geodetic Survey, Special Publication No. 5, 1900.

ON THE RELATION OF PYRRHOTITE TO CHALCOPYRITE AND OTHER SULPHIDES.

ARTHUR PERRY THOMPSON.

INTRODUCTION.

The presence of copper ores in the metamorphic rocks of the states along the Atlantic seaboard has been known since the early part of the last century. The deposits have been frequently described. By one author and another they have been placed under different types. Thus, they have been regarded as beds, later in age than the footwall and older than the hanging; they have been considered segregated veins; and finally, they have been regarded as fissure veins, pinched into lenses during metamorphism. Most commonly the country rock of the mining regions is a schist. When this is the case the origin of the orebodies is involved in some obscurity and they are usually classified with respect to their physical characteristics and mineralogy.

Among early writers on these deposits A. F. Wendt[1] gives an interesting account. J. D. Whitney in "The Metallic Wealth of the United States"[2] has reviewed the sulphide deposits in the East and later has especially described the deposits of Ducktown, Tennessee. The excellent paper by Carl Henrich,[3] together with later contributions by J. F. Kemp,[4] W. H. Weed[5] and W. H. Emmons[6] have made the observations on Ducktown much more

[1] "The Pyrite Deposits of the Alleghanies," *School of Mines Quarterly*, Vol. 7, 1886.

[2] J. D. Whitney, "Remarks on the Changes that Take Place in the Structure and Composition of Mineral Veins," *Amer. Journ. Sci.*, Vol. XX., 53.

[3] "The Ducktown Deposits and the Treatment of the Ducktown Copper Ores," *T. A. I. M. E.*, XXV., 173, 1895.

[4] "Order of Formation of Minerals in Ducktown Veins," *T. A. I. M. E.*, 1899; "Deposits of Copper Ores at Ducktown," *T. A. I. M. E.*, XXXI., 244.

[5] "Types of Copper Deposits in the Southern United States," *T. A. I. M. E.*, Vol. XXX., 1900, 449; "Copper Deposits of the Appalachian States," Bull. 455, U. S. G. S.

[6] "Metamorphosed Ore Deposits," ECON. GEOL., 1909, Vol. 4, 775.

complete than upon any other eastern deposit. H. S. Wheeler[1] has described the Vermont copper deposits, particularly the Ely Mine. W. H. Emmons[2] and W. H. Weed[3] have contributed results of later observations and studies of the deposits in the Appalachian states.

The data given below are the result of a study of specimens from ore-bodies of the following localities (in most cases the associated sulphide was pyrrhotite): Ducktown, Tennessee; Vershire, Vermont; Eustis, Quebec; the Union and Clegg mines, North Carolina; and Gordonsville, Virginia. A comparative examination has also been made of the ore from the "Big Bonanza" Mine, La Touche Island, Alaska.

The object of this study has been to determine the relation of pyrrhotite and chalcopyrite and the order of introduction and crystallization of these and any other sulphides which might be present. No attempt has been made to distinguish different minerals of the gangue—they will be referred to hereafter simply as gangue.

THE DEPOSITS OF DUCKTOWN, TENN.

The Ducktown deposits have been described by numerous authors and different views have been advanced concerning their genesis. Later writers have generally agreed, however, that the ore-bodies are lenticular in shape. As a rule they are parallel to the schistose country rock, but in some instances they cut the schistosity. Several lime silicates of which garnet and zoisite are chief have resulted from a probably calcareous original. There has been much crushing and compression where the ore is now found. Later, mineral-bearing solutions entered, probably replacing the finely crushed country rock and the silicates. The solutions deposited in the Burra Burra, pyrite and later, pyrrhotite and chalcopyrite. Elsewhere pyrrhotite and chalcopyrite were introduced, the latter probably later and after an intermediate movement of the walls. Zincblends occurs in minor

[1] "Copper Deposits of Vermont," *School of Mines Quarterly*, Vol. 4, 219; "The Pyrrhotite of the Ely Mine," *Eng. and Min. Jour.*, April 10, 1886, 263.

[2] "Metamorphosed Ore Deposits," ECON. GEOL., 1909, Vol. 4, 755.

[3] "Copper Deposits of the Appalachian States," Bull. 455, U. S. G. S.

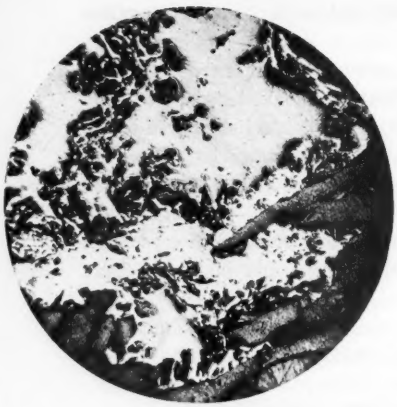


FIG. 54.

KEY TO FIG. 54.

FIG. 54. ×45. (*a*) Polk County Mine ore, Ducktown, Tenn. Pyrrhotite and chalcopyrite traversing blende in veinlets.

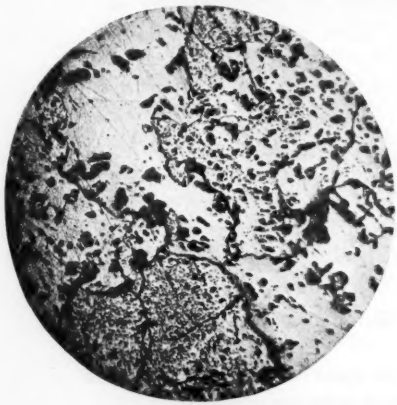


FIG. 55.

KEY TO FIG. 55.

FIG. 55. ×45. Mary Mine ore, Ducktown, Tenn. Pyrrhotite cut and corroded by a veinlet of chalcopyrite.

amount at the Mary Mine and with galena is probably later than pyrrhotite and chalcopyrite.

In the present investigation, specimens were examined from the Polk County Mine and the Mary Mine. The order of origin of the sulphides from the study by this method has proved to be: (1) Blende; (2) pyrrhotite; (3) chalcopyrite. Pyrite was not observed in the specimens and galena occurred in such small amount that its relationship was obscure.

Specimens from the Polk County Mine consisted of crystalline and irregular masses of shattered gangue. The interstices were filled with the metallic sulphides. There had been evident replacement of the gangue by the metallic sulphides. Zincblende was the chief sulphide to be deposited. Pyrrhotite and chalco-

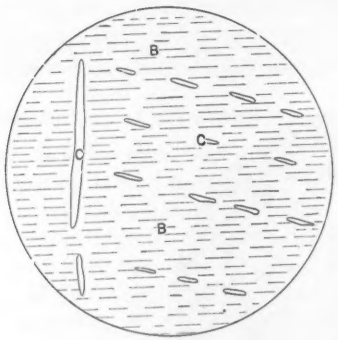


FIG. 56. × 50. Streaks and dots of chalcopyrite through blende.

pyrite are found traversing the blende in numerous veinlets, as illustrated by Fig. 54.

A characteristic feature of the blende is the occurrence of many fine, straight and parallel streaks of pyrrhotite and chalcopyrite through it and the parallel arrangement of many small included dots of the same minerals, as shown in Fig. 56. It is evident that the last two sulphides have penetrated the blende

along strain and cleavage cracks and when the polished face has cut the minute veinlets parallel to their elongation, fine straight lines of the sulphides are seen; when perpendicular to the veinlets, the section exposes parallel arrangements of dots of the two minerals. Viewed under the microscope with reflected light the different minerals are characterized by colors which make them much more readily distinguishable than they appear in the microphotographs. Blende gives, when well polished, a smooth blue surface. Chalcopyrite will also polish smooth and appears as a bright brass-yellow mineral. Pyrrhotite, generally more pitted on account of its brittleness, has a distinctive light bronze color.

Fig. 55 shows pyrrhotite cut and corroded by a veinlet of chalcopyrite. Subsequent to the deposition of most of the pyrrhotite there occurred a fracturing of the mineral which permitted the infiltration of solutions, bearing chalcopyrite. In the cracks thus produced in the blende and pyrrhotite, chalcopyrite has been deposited. It further favors the contact of pyrrhotite and blende and is especially prominent around the edges of blende and gangue. The contacts of these minerals, parted during fracture, have afforded the most convenient channels for the circulation of the solutions.

From the intimate association of pyrrhotite and chalcopyrite in places there appears to have been an overlapping of the periods of their deposition. Thus, after the crushing of the blende and pyrrhotite, a minor amount of pyrrhotite was deposited along with the chalcopyrite.

The ore from the Mary Mine is mottled with minor amounts of galena and zincblende. Galena occurred in such small quantity that its relations to the other sulphides could not be determined. Blende, however, was found in isolated patches in chalcopyrite, showing irregular boundaries, due to the attack of the later solutions. One can also observe the characteristic dots of chalcopyrite. Pyrrhotite was found in similar relationship to chalcopyrite as in the Polk County Mine ore.

Fig. 57 shows a common instance of the impregnation of pyrrhotite by chalcopyrite.

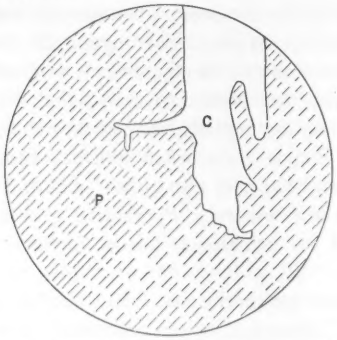


FIG. 57. ×50. Chalcopyrite cutting through pyrrhotite in stringers.

In the polished sections from the Mary Mine as in those from the Polk County Mine, the order of deposition has been: (1) Blende; (2) pyrrhotite; (3) chalcopyrite.

Summary on the Ducktown Ore.

(*a*) In all of the specimens examined, crushed silicates have been attacked and replaced. There is further a definite order of succession in the precipitation of the sulphides. It is: (1) Blende; (2) pyrrhotite; (3) chalcopyrite.

(*b*) The blende and pyrrhotite have been strained and fractured and permeated by a minor amount of pyrrhotite and much chalcopyrite.

(*c*) The minerals in the above order seem to have replaced each other. In the case of pyrrhotite and chalcopyrite, at least, there has been an overlapping of the periods of deposition.

THE DEPOSITS OF THE VERSHIRE (ELY) MINE, VT.

The country rock at Vershire is biotite schist greatly folded and cut by granite. The ore deposit has been described by W. H. Weed.[1] It is composed of two lenticular masses conformable to

[1] "Copper Deposits of the Appalachian States," Bull. 455, U. S. G. S.

the foliation of the enclosing schist. The ore-bodies average 100 feet along a N. and S. strike, 10 feet in thickness and 100 to 300 feet along the dip of 24 degrees. The ore minerals are pyrrhotite, chalcopyrite, some pyrite and zincblende. The gangue is quartz, actinolite and garnet. Biotite is very common in the ore, frequently in groups of elongated shreds.

The polished surfaces of this ore showed chalcopyrite as the predominant mineral. Zincblende, pyrrhotite and gangue complete the list of minerals. Before the entrance of mineral-bearing solutions, the silicates were subjected to considerable crushing. Later, with the coming of solutions bearing the metallic sulphides,

FIG. 58. × 50. Crystallized pyrrhotite in matrix of chalcopyrite.

blende was first deposited, around the margins of the gangue and in minute cracks through it. Without further movements in the deposit, pyrrhotite was precipitated surrounding particles of gangue and bordering blende. In some instances it penetrated the blende. Pyrrhotite occurs in good crystalline form surrounded by chalcopyrite as shown in Fig. 58.

A period of crushing ensued after the deposition of pyrrhotite and later came the infiltration of solutions bearing chalcopyrite. The latter mineral was found penetrating the gangue, blende and pyrrhotite, filling cracks and replacing the other minerals. Fig. 59 shows chalcopyrite cutting through pyrrhotite and entering it in little veinlets.

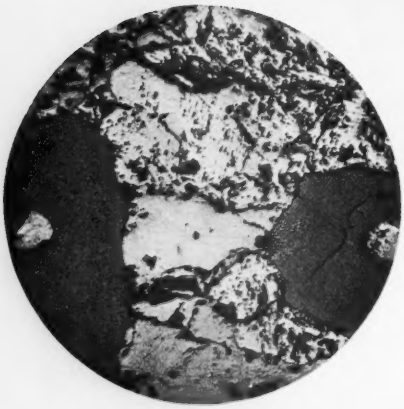


FIG. 59.

KEY TO FIG. 59.

FIG. 59. ×45. (*c*) Veinlets of chalcopyrite cutting through pyrrhotite in ore from Vershire, Vt.

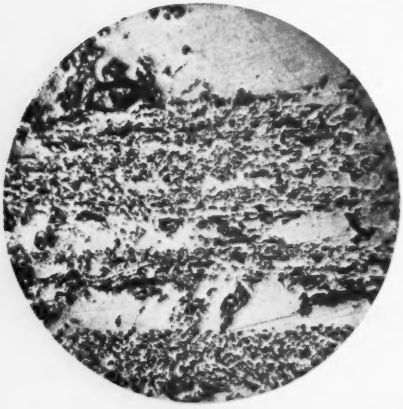
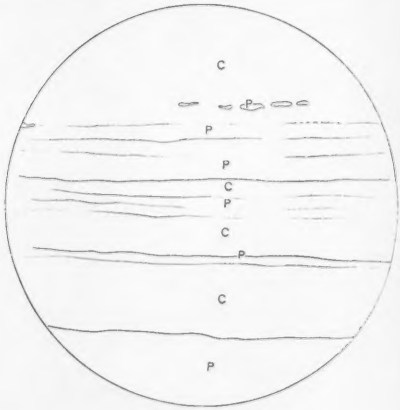


FIG. 60.



KEY TO FIG. 60.

FIG. 60. ×45. Shows narrow strips of pyrrhotite surrounded by chalcopyrite. Vershire, Vt.

It is evident that there occurred more or less replacement of the gangue minerals by the solutions of the metallic sulphides. Further, the solutions bearing pyrrhotite appear to have impregnated and replaced blende, while solutions bearing chalcopyrite later replaced and impregnated both shattered blende and pyrrhotite.

Other sections show a very small amount of blende and abundant pyrrhotite and chalcopyrite, filling cracks and replacing the gangue minerals. Fig. 60 shows narrow strips of pyrrhotite surrounded by chalcopyrite. The pyrrhotite has replaced narrow strips of gangue or has entered between them and has been deposited there. Subsequently, following a period of crushing, the solutions bearing chalcopyrite, by either filling or replacing the intervening space or gangue with the copper-iron sulphide, have helped preserve the structure of the original minerals. Fig. 61 illustrates the well-developed cracks through pyrrhotite

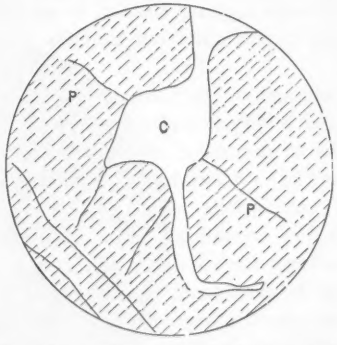


FIG. 61. × 50. Chalcopyrite veinlet in pyrrhotite.

found filled with chalcopyrite. Finally, the ore suffered a fracturing which admitted solutions depositing quartz in minute veinlets.

From the examination of these sections it may be said that:

(*a*) The gangue was subjected to a considerable crushing and later, solutions of the metallic sulphides entered the crushed zone

and precipitated the sulphides, replacing more or less of the silicates.

(*b*) Blende was the first sulphide to be laid down and was followed by pyrrhotite.

(*c*) Subsequent to the deposition of pyrrhotite, a crushing occurred which permitted the precipitation of the last sulphide, chalcopyrite, through cracks in the earlier minerals. Later disturbances have admitted solutions depositing quartz through the ore in small amounts.

THE EUSTIS MINE, CAPELTON, QUEBEC.

Little has been written about the Eustis deposit. From a published description by J. E. Dresser[1] and a statement by Major Leckie[2] the following summary is written: The country rock is schistose but somewhat variable. A considerable proportion was probably originally a diabase and the greater part was amygdaloidal. The lode, which conforms to the schistosity of the rocks, is a lens-shaped mass varying from 6 to 40 feet in thickness. The ore is highly pyritiferous, but contains copper and 1 to 3 ounces of silver.

Numerous specimens of the Eustis ore examined proved to be chiefly pyrite, with a very interesting group of subordinate minerals. The order of deposition of the sulphides proved to have been: (1) Pyrite; (2) zincblende; (3) tetrahedrite; (4) bornite; (5) galena; (6) chalcopyrite.

The pyrite is well crystallized. It has suffered fracture and through the fractures the solutions of the later sulphides have circulated, filling the cracks and replacing the pyrite. After the crushing, gangue minerals were deposited to a small extent and blende was precipitated in many places with crystalline form. Fig. 62 shows blende surrounding crystals of pyrite. Fig. 63 shows blende bordering pyrite. One may see well defined crystal faces of blende surrounded by bornite. On account of its hardness, pyrite retains scratches after the remainder of the section is well polished. It also stands out in relief from the softer enclosing minerals.

[1] *Jour. Can. Min. Inst.*, Vol. 5, 1902, 81–86.
[2] *Jour. Can. Min. Inst.*, Vol. 7, 1904, 400.

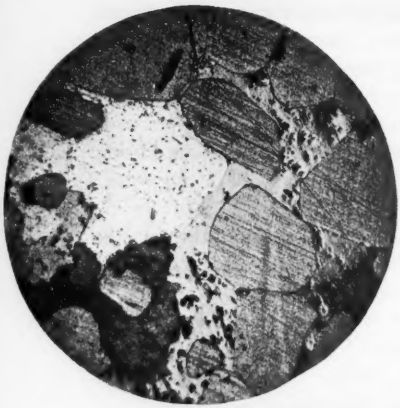


FIG. 62.

KEY TO FIG. 62.

FIG. 62. × 45. Galena surrounding crystalline pyrite and blende. Pyrite enclosed in blende, bornite and stringers of chalcopyrite. Ore from the Eustis Mine, Quebec.

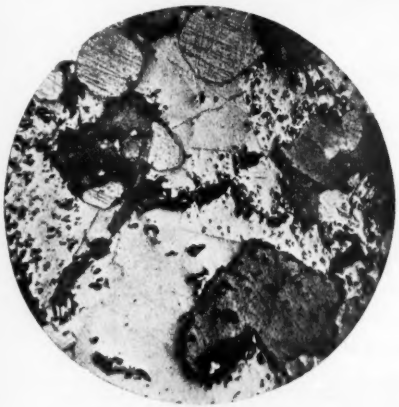


FIG. 63.

KEY TO FIG. 63.

FIG. 63. × 45. Chalcopyrite veinlets through the bornite of the Eustis Mine ore. Crystalline sphalerite formed around pyrite and in turn coated with bornite.

Tetrahedrite occurs surrounding crystal faces of blende and traversing cracks through the latter. Bornite, in turn, has eaten its way into tetrahedrite, showing that it has followed the latter in order of formation.

Fig. 63 shows characteristic smooth polished faces of bornite surrounding the lighter and more pitted surfaces of zinc-blende. Through the bornite, veinlets of chalcopyrite may be distinguished.

In Fig. 62 chalcopyrite can with difficulty be seen cutting through the bornite. Viewing the polished surfaces through the microscope and in reflected light, the two minerals are very readily distinguished by their color, chalcopyrite presenting a bright brass-yellow surface, bornite a pinkish brown. There appeared to be bornite of two shades of brown, the lighter colored apparently later than the other. Similar differences have been observed in the bornite from Butte, Montana.

Fig. 62 presents galena surrounding crystalline pyrite and blende and in contact with bornite. It has come in after the

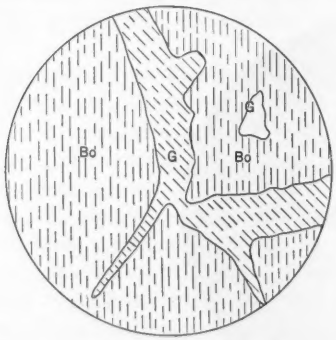


FIG. 64. × 50. Galena veinlet in bornite.

bornite was deposited, as instanced by many crack fillings in the bornite and replacements. See Fig. 64. The galena is found at times in very intimate contact with the chalcopyrite. Although the evidence points to the fact that the chalcopyrite has been the last mineral to form, there seems to have been an overlapping of the periods of deposition of the two sulphides.

Galena shows a strong tendency to crystallize at all times. It presents a dazzling white surface by reflected light and shows a very light color in the photograph.

Chalcopyrite fills cracks cutting through the galena and seems to have especially impregnated the bornite with traversing veinlets and replacements. A very characteristic case is a stringer of chalcopyrite passing through bornite as is shown in Fig. 65.

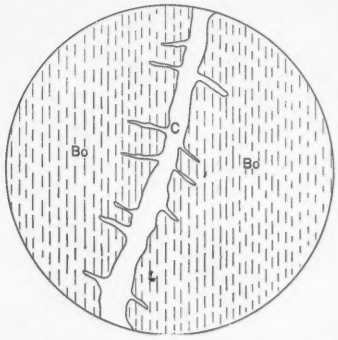


FIG. 65. × 50. Chalcopyrite veinlet through bornite.

In all of the specimens examined the same order of origin has been traced: (1) Pyrite; (2) blende; (3) tetrahedrite; (4) bornite; (5) galena; (6) chalcopyrite. Thus it is seen that when pyrrhotite is lacking, the other sulphides bear about the same relation to each other. The silver reported in the ore is in too small a quantity to distinguish with the microscope. It is probable that it occurs in the galena or the tetrahedrite.

THE NORTH CAROLINA DEPOSITS.

The Union Mine.—This deposit belongs to the "Gold Hill Type" as classified by W. H. Weed.[1] The country rock is an argillaceous metamorphic schist. Fissure veins of auriferous quartz occur parallel to the foliation of the schist. The ores show

[1] "Types of Copper Deposits in Southern U. S.," *T. A. I. M. E.*, Vol. 30, 1900, p. 470.

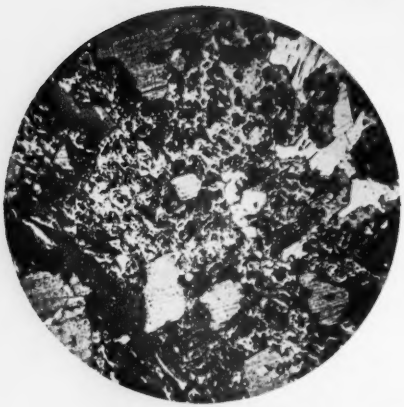
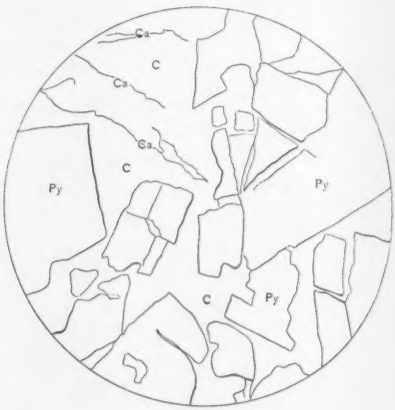


FIG. 66.

KEY TO FIG. 66.

FIG. 66. ×45. Ore from the Union Mine, North Carolina. Pyrite crystals in a matrix of sphalerite. Galena and chalcopyrite ramifying through the blende.

FIG. 67.



KEY TO FIG. 67.

FIG. 67. ×45. Interstices between shattered crystalline pyrite, filled with chalcopyrite. Minute stringers of chalcocite in chalcopyrite, Union Mine ore.

no banding but exhibit a brecciated structure, the schist breccia being replaced by quartz or the ferro-magnesian minerals by ore. There are no definite walls to the fissure. After the crushing of the silicified schist and pyrite, according to Weed, chalcopyrite together with a little galena, blende and new quartz have been deposited.

Study of ore from the Union Mine has corroborated Mr. Weed's conclusions. Crystalline pyrite, older than any other sulphide present, has been subject to crushing. Fig. 67 shows the characteristic structure of pyrite surrounded by chalcopyrite. Following this movement, gangue minerals were precipitated in the crushed mass and later zincblende was deposited. The blende is shown in Fig. 66, where it has surrounded and replaced portions of pyrite crystals. Galena and chalcopyrite are in turn seen ramifying through the blende. The latter mineral presents a rough pitted surface in the photomicrograph and is with difficulty distinguished from chalcopyrite. Under the microscope, with reflected light, the polished surfaces of the two minerals afford colors that readily distinguish them.

Thus, it is seen that blende has followed the pyrite: chalcopyrite and galena have been deposited in the order named with perhaps an overlapping of periods of deposition suggested by their intimate associations in places. Finally, the chalcopyrite is found traversed by minute stringers of chalcocite, as shown in Fig. 67. These tiny veinlets of chalcocite represent the alteration and secondary enrichment of the ore.

The Clegg Mine.—The greater part of polished sections of this ore proved to be chalcopyrite. Within the chalcopyrite well-crystallized but crushed gangue was found, as shown in Fig. 69. Blende occurs in small amount, much eroded and penetrated by extremely fine specks of chalcopyrite.

The most notable feature of this ore is its decomposition. The chalcopyrite has been subjected to strains which have produced much minute fracturing. In these fractures and others that are largely emphasized by decomposition, the secondary products are found. The tendency of the cracks has been to form radially

with particles of gangue as centers. Fig. 68 shows a magnification of cracks filled with secondary products radiating from small crystals of gangue.

Alteration is confined chiefly to the chalcopyrite. On account of the very minute size of the cracks, much definite data could not be gathered concerning their contents. By means of etching with HNO_3 the characteristic roughness of chalcocite was obtained. Bornite also appears frequently. Both of these sulphides are present as very fine films on the walls of the cracks. Covellite

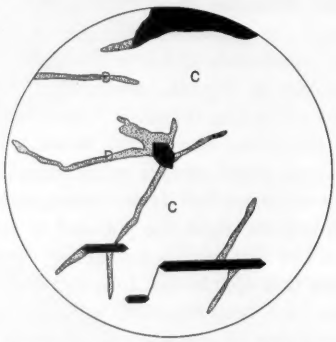


FIG. 68. × 50. Decomposition products in cracks through chalcopyrite.

was distinguished in isolated grains. Fig. 69 shows hardly distinguishable cracks filled with secondary sulphides ramifying through chalcopyrite.

These specimens from North Carolina bear out the same order of origin of the sulphides as found in the preceding cases. That order is: (1) Pyrite; (2) blende; (3) chalcopyrite; galena seems to be variable in its position.

THE DEPOSITS NEAR GORDONSVILLE, VIRGINIA.

Gordonsville lies on the eastern slopes of the Southwest Mountain range. The ore-bodies of the Southwest Mountain region have been described by W. H. Weed.[1]

[1] "Copper Deposits of the Appalachian States," Bull. 455, U. S. G. S.

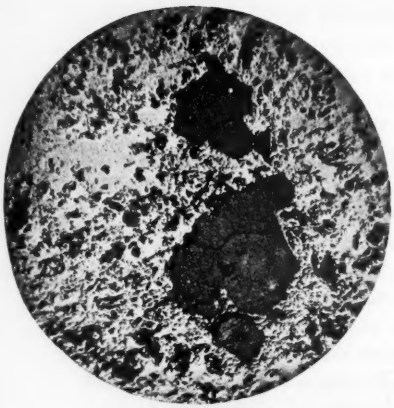


FIG. 69.

KEY TO FIG. 69.

FIG. 69. ×45. Ore from the Clegg Mine, North Carolina. Crushed crystalline gangue in a mass of chalcopyrite. Small cracks with secondary sulphides.

FIG. 70.

KEY TO FIG. 70.

FIG. 70. ×45. Crushed pyrite in the ore from Gordonsville, Va., cemented with blende, pyrrhotite, chalcopyrite and galena.

Examinations of polished sections of the ore showed pyrite, blende, pyrrhotite, chalcopyrite and galena in this succession. Pyrite as in other cases has been subjected to crushing. Solutions bearing gangue then entered and deposited their minerals between the crushed fragments of pyrite. Next, blende was introduced, in many cases in contact with the gangue and on the crystal faces of the minerals. The blende also fills shattered zones of the pyrite and replaces it in part.

Fig. 70 illustrates crystalline and crushed pyrite with its customary scratched surface. Surrounding the pyrite is gangue, blende, pyrrhotite, chalcopyrite and galena.

Pyrrhotite occurs in irregular patches traversing the pyrite, blende and gangue. Chalcopyrite has followed, entering the pyrite and attacking its edges. It occurs coursing through the

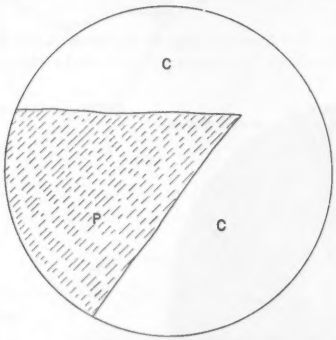


FIG. 71. × 50. Crystallized pyrrhotite surrounded by chalcopyrite.

gangue and the blende, as well as the pyrrhotite. Fig. 71 shows enlargement of a crystal of pyrrhotite in contact with chalcopyrite.

The relation of galena to the other sulphides is obscure, since it is present in such small quantity. It has come in, however, later than the quartz. Chalcocite, the result of secondary enrichment, occurs as fine films in minute cracks and along lines of decomposition in the pyrite, pyrrhotite and chalcopyrite.

Thus it is seen that in this locality the same relationship of the sulphides is found, viz., (1) Pyrite, (2) blende, (3) pyrrhotite, (4) chalcopyrite.

THE "BIG BONANZA" DEPOSITS, LA TOUCHE ISLAND, ALASKA.

The "Big Bonanza" copper mine has been described by F. C. Lincoln.[1] The sections examined support Lincoln's conclusions with respect to the occurrence of the ore. There has been replacement and impregnation of, and filling of cavities in, brecciated masses of slate or graywacke.

Study of the different types of occurrence of the ore has led to conclusions regarding the succession of the minerals somewhat different from those reached by Mr. Lincoln. Pyrite, in the polished sections, is the oldest of all the sulphides. It is found well crystallized, bounded with and traversed by cracks filled with all the other minerals. The main part of the gangue was next to come in after a fracturing of the pyrite. The gangue shows very rough and irregular edges, due to the solvent action of later mineral-bearing solutions. This is illustrated by Fig. 73.

Blende is found along the edges of the gangue and in isolated patches surrounded by pyrrhotite and chalcopyrite. Fig. 73 shows an instance of the occurrence of blende. Cracks through the sphalerite show pyrrhotite filling. In Fig. 72 crushed crystals of pyrite are bordered by blende, pyrrhotite coming in later and surrounding both. Pyrrhotite is also found along the eroded edges of gangue as in Fig. 73, and in seams and irregular bodies in masses of chalcopyrite.

It appears that the deposition of pyrrhotite began before that of chalcopyrite. Evidently the faces of the gangue minerals were most favorable to the precipitation of pyrrhotite and here it is found along the contact of gangue and chalcopyrite. In places the chalcopyrite is found eating into the pyrrhotite which in turn projects away from the gangue into the chalcopyrite.

[1] ECON. GEOL., Vol. IV., p. 201.

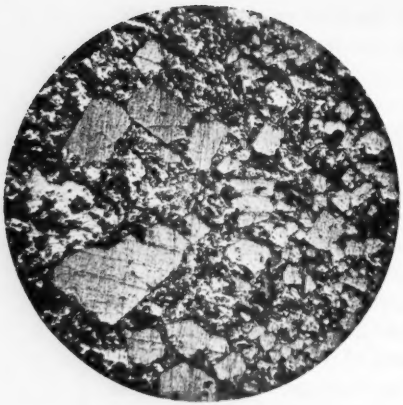


FIG. 72.

KEY TO FIG. 72.

FIG. 72. ×45. La Touche Island, Alaska, ore. Crushed pyrite cemented with blende, pyrrhotite later than both.

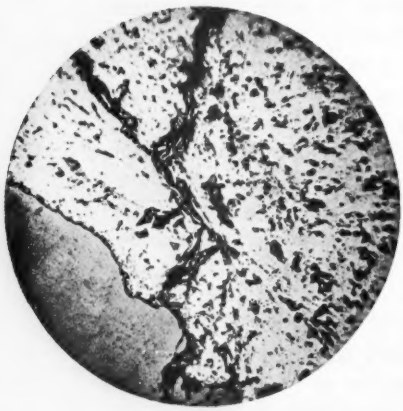


FIG. 73.

KEY TO FIG. 73.

FIG. 73. ×45. Corroded mass of gangue in contact with pyrrhotite and chalcopyrite. Irregular patches of sphalerite in chalcopyrite in specimen from La Touche Island.

Irregular and roughly parallel bodies and narrow strips of rounded pyrrhotite are found in large areas of chalcopyrite. This occurrence has led to the conclusion that the pyrrhotite-laden solutions entered the country rock and gangue first, along roughly parallel lines of strain and fracture, and then replaced the material most susceptible to solution. Later solutions carrying chalcopyrite replaced the country rock, or gangue, surrounded the pyrrhotite, and left it in isolated patches.

It is quite probable that the deposition of pyrrhotite had not been concluded before chalcopyrite began precipitating. Indeed, there seems from many of the occurrences of the two minerals, to be no other possible conclusion except that there was an overlapping of the periods of deposition of the two minerals, with pyrrhotite definitely first.

The order of origin observed in these specimens will then be: (1) Pyrite, (2) gangue, (3) blende, (4) pyrrhotite, (5) chalcopyrite.

Mr. Lincoln's order was: (1) Sphalerite, (2) chalcopyrite, pyrrhotite and pyrite, (3) ankerite, (4) quartz.

CONCLUSIONS.

As a result of the metallographic examination of these specimens from widely separate mining regions, interesting conclusions may be drawn:

I. The order of origin of the metallic sulphides has been strikingly similar in all of the ores. That order is:

1. Pyrite,
2. Blende,
3. Pyrrhotite,
4. Chalcopyrite.

II. The relation of pyrrhotite and chalcopyrite in some instances is very close, pyrrhotite, however, being distinctly the first to form.

III. Galena is somewhat variable in its occurrence, but is usually formed as one of the later sulphides.

IV. The periods of deposition of the sulphides are not necessarily distinct and separate phases of the formation of the ore. The association of two or more sulphides may be so close that their relative ages are impossible to ascertain. Overlapping of periods may occur, giving no definite clues as to the ages of the sulphides.

V. Solutions of the later sulphides have in turn generally replaced and impregnated the earliest sulphides as well as the gangue. Chalcopyrite has been particularly active in this respect. To a less degree galena does the same. Quartz gangue has been repeatedly corroded and replaced by later solutions bearing the metallic sulphides.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

"SECONDARY SILICATE ZONES": A REPLY TO CRITICISMS BY J. F. KEMP AND C. A. STEWART.

Sir: In Volume VIII., Nos. 5 and 6 of ECONOMIC GEOLOGY, there appeared two rather severe and unfavorable criticisms of my paper on limestone-contacts—one by Prof. J. F. Kemp and the other by Mr. C. A. Stewart. I regret in the first place that the chief point of my thesis has apparently escaped my critics, and in the second place, that they have evidently considered the tone of my paper as somewhat personal. Anything in the nature of personalities was entirely unintentional, and I gladly take this opportunity to disclaim any feeling of that sort. The reader may be pardoned for misinterpreting my meaning in places where the language is not very clear, but I hope that the presentation of the material that follows will do away with any misunderstanding that may exist as to my position with regard to contact metamorphism.

As I am at present engaged in field work, some of the literature on the subject, as well as the time required to make a detailed reply, are not at present available, but I offer a brief restatement of the main thesis of my paper, accompanied by some additional data on the subject.

The hypothesis of the recrystallization of impurities in the limestone to form the "secondary silicate" zones, as presented

in my paper, emphasized the two-phased action in such metamorphism. On page 227 of my paper (ECON. GEOL., Vol. VIII., No. 3) there appears the following statement:

"From the point of view of the recrystallization hypothesis, it is admitted that these mineralizing gases play an important part in the formation of the second phase of the metamorphic zone, but it is maintained that this period of emission is decidedly later than that of the formation of the first phase."

On page 25 is found the following:

"This view [recrystallization hypothesis] does not by any means involve a total absence of infiltrated material from the intrusive, but its advocates maintain that the so-called contact-zone can be lithologically divided into two parts, one part of which is formed by recrystallization in the early stages of metamorphism, and the other part by later addition of material in the way of emanations from the magma."

In the face of the above statements, Mr. Stewart writes:

"If one admits, as does Mr. Uglow, that waters do issue from the intrusive, he surely will be hard pressed for an explanation of their inability to carry in solution some of the elements contained in the rocks through which they have passed."

The whole purpose of my paper was to point out that, in these days when so much in the way of direct contribution and emission was attributed to intrusives, it would be well to remember the influence of other agencies and to keep the whole series of processes in proper perspective.

Recrystallization has especial reference only to the first phase of contact action. A fluid magma, probably well above its temperature of crystallization, rises up gradually through a series of sedimentary rocks, by any combination of the well-known methods—overhead stoping, hoisting aloft, thrusting aside, and marginal assimilation. Its progress is slow and long periods of time are available for the heating of the country rocks. It is during this time, before the intrusive gets to a stationary position and crystallizes in toto, that the elimination of the excesses constituents and the recrystallization of impurities in the limestone is inferred to take place. This is the period to which the dia-

gram on page 230 (ECON. GEOL., VIII., 3) applies. The pressure that is exerted on the limestone may accomplish its results before the potentially continuous advance of the magma is completed. The hypothesis says nothing of any re-advance. As the elimination of the constituents from the limestone takes place, the fluid magma forces itself upward, and the heat waves keep up a continuous advance into the region ahead. During this period of the advance of the magma, the limestone in its immediate neighborhood is becoming progressively fractured and more porous, and these openings afford means of escape for the eliminated materials.

As the magma cools and crystallizes, a state of tension is set up in the igneous mass and the neighboring rocks. Tension fractures result, extending from the intrusive into the limestone. At the same time, the limestone farther away from the intrusive is receiving fresh accessions of heat due to the progress of the heat waves that left the intrusive long before. Hence while the outward part of the limestone may still be under compression and be recrystallizing, the inner part, already recrystallized, is being broken by tension fractures. It is believed to be during this later period when the outer shell at least of the intrusive has become crystallized, that the fractures provide channels for the escape of the main body of the constituents from the magma —silica, alumina, iron oxides, metallic compounds, or whatever they may be. In any one zone surrounding the intrusive the two periods of recrystallization and infiltration may or may not be sharply differentiated. Essential to the above view is an understanding of the slow progress of the heat wave from the magma into the surrounding limestone, as so well developed by Dr. L. R. Ingersoll.[1]

In my first paper the term "secondary silicates" (in quotation) was used with reference strictly to the products of the first phase of contact metamorphism, that is, the products of recrystallization; while the expression, contact zone (not in quotation), was

[1] L. R. Ingersoll and O. J. Zobel, "An Introduction to the Mathematical Theory of Heat Conduction with Engineering and Geological Applications," 1913.

applied to the whole mass of contact metamorphosed limestone. As printed in ECONOMIC GEOLOGY, this distinction was not made clear on account of an incorrect use of quotation marks. In the reprints which were distributed, however, the necessary corrections appear. The list of minerals appearing under Group 2, page 22, of the original article, should of course be enlarged to include some garnets, pyroxenes, amphiboles, etc., which are sometimes products of the second phase of contact action.

Undoubtedly, in the great number of cases of contact action that have been described, the two processes have varied greatly in their relative strength and influence. Indeed, when the second, or infiltration process, was exceedingly potent, the materials emitted may have largely replaced and so destroyed the results of the first process. But such action does not preclude the possibility of the first process having been important. This hypothesis leaves room for vein-filling, replacement, "pegmatite-like" deposition, etc., during the second phase of contact action.

Since the original paper was prepared, very little further work has been done by the writer on the subject; but a few additional illustrations of the importance of the recrystallization phase have been met with. Quotations are made below from the literature in which these illustrations are contained:

1. A close analogy to the formation of these "secondary silicate zones" is afforded in the Lake Superior district by the production of amphibole-magnetite rocks by contact metamorphism of cherty iron carbonates. In this case the alteration is believed to be due to recrystallization of materials originally in the iron formation, rather than to introduction of constituents from the intrusive gabbro, for the following reasons:[1]

(*a*) The average chemical composition as measured by an exceptionally large number of quantitative determinations, is not essentially changed except by dehydration, and perhaps locally by introduction of sulphur or other constituents.

(*b*) The alterations of the carbonate and greenalite rocks have produced amphibole-magnetite rocks. The alterations of the ferruginous cherts and soft ores have produced banded red jaspers and hard ores.

(*c*) The magnetite in the gabbro is titanic, while that in the adjacent iron formation is not.

[1] U. S. Geol. Survey, Mon. 52, pp. 546, 554.

(*d*) There is no regular variation in the composition of the metamorphic phases of the iron-bearing formation through the several hundred feet from the contact for which these phases are known in many places to extend.

(*e*) The very fact that the metamorphic phases of the iron formation extend so far and so uniformly from the gabbro contact argues against their development by accession of materials from the intrusive.

(*f*) In thin sections of cherty iron carbonate rocks from the Lake Superior district which have been only slightly anamorphosed, thin bands of amphibole needles (chiefly grünerite and actinolite) are found abundantly near the contacts of the chert and the carbonate laminae. This is good evidence of recrystallization in situ.

2. The following facts are taken from an article by Spurr, Garrey and Fenner on the Matehuala district, Mexico:[1]

(*a*) "The south margin of the Cobriza area alteration is marked by the metamorphism of the shale bands to hornstone containing disseminated pyrite and small crystals of white grossularite garnet. These alternate with unaltered blue limestone bands and begin at a distance of 400 meters from the nearest intrusion, which is not large. This is apparently metamorphism mainly by regeneration" (pages 455–456).

(*b*) "The law may be deduced for this Cobriza area that as the distance from the metamorphic center (or the intrusion) increases, metamorphism by regeneration increases relatively to metamorphism by addition and total replacement" (page 456).

(*c*) "The chert bands in the limestone are altered to wollastonite, from the margins inward. This was even noted near the Dolores mine at a point sufficiently far from the intrusion that no other metamorphism was noticed. The narrow vein of wollastonite forming in the chert next the limestone here seems to represent metamorphism by reaction—a variation of metamorphism by regeneration" (page 461).

(*d*) The authors have worked out in considerable detail the paragenesis of the minerals of the contact zone. The minerals fall into eight groups, but it is significant to notice that at the end of the third group there seems to be a very important natural break in the succession. These groups in the order of their formation are as follows: (1) pale green aluminous pyroxene, (2) pale red brown grossularite garnet, (3) wollastonite, (4) dark green pyroxene (hedenbergite), (5) dark (andradite) garnet, (6) quartz, fluorite, and cupriferous pyrite, (7) metallic sulphides other than those of iron and copper, (8) calcite.

"The earlier lime silicates were formed in crushed and shattered rock, and there is abundant evidence that this provided openings along which they rose and circulated. There appear, however, to have been few

[1] ECON. GEOL., Vol. VII., 1912, p. 444.

definite channels. The zones followed by the hedenbergite show the initiation of some persistent fissuring previous to the advent of this mineral. . . .As the amount of hedenbergite deposited was vastly less than that of the earlier silicates, its localization along contacts on account of the preexisting fissures makes it more nearly a 'contact' mineral than the older ones. . . .The minerals of the quartz-fluorite-metallic sulphide stage form numerous fissure veins in the monzonite transverse to the contact, and are capable of important subdivision as to age. The fissures of this period also occurred along and parallel with the contact, and therefore the materials of this stage mingled with or replaced the earlier minerals, or were deposited as plain veins cutting through them" (pages 457–466).

This example gives excellent evidence of the two-phase notion of the contact zone—the first stage being one of compression, rock-shattering and recrystallization, the second a period of tension, rock-fissuring and infiltration.

3. At a distance from the contact the metamorphic rock of the Marysville district is a banded hornfels consisting of biotite, tremolite, quartz, feldspar, calcite, and zoisite. This rock is believed to have been produced by the first wave of metamorphism. Veinlets of epidote, bleaching the biotite along their contacts, cut the hornfels and are due to a later infiltration of material from the granitic magma. (U. S. Geol. Survey, Prof. Paper, 57.)

According to Mr. Stewart, the chief point of my paper is that a "comparison of the analyses of fresh and metamorphosed limestones shows little variation in the respective ratios of silica, alumina, and iron." Although I did not consider this the chief point of the paper, a few of Mr. Stewart's criticisms of the treatment of this subject deserve further mention here. It is true that attention was called to the slope of the lines and their slight departure from the perpendicular, but care was taken to state that the slopes indicated only *relative* changes in the amounts of the oxides.

Mr. Stewart recasts my results from the comparison of the analyses of fresh and altered limestones, and states that, instead of there being an approximate constancy in the ratios of silica alumina, and iron, in 5 out of the 7 cases there is a variation of from 20 to 700 per cent. Here, again, he has confused absolute with relative values. With respect to the differences shown by the

potash, soda, magnesia, water, lime, and carbon dioxide ratios, there certainly is an approximate constancy in the silica, alumina, and iron ratios. In all cases except that of Hastings County and Iron Springs the analyses are incomplete. Only with complete analyses and accurate sampling, so as to eliminate from the metamorphosed type all those minerals belonging to the second or infiltration phase of contact action (as was done in the two cases above cited), will dependable results be obtained. Whenever the geology of the specific area admits, samples of the "secondary silicate" zone should be taken only from those portions of the rock that are the product of the first phase of metamorphism.

Some of the criticisms of Professor Kemp will be taken up about in the order in which they occur in his paper. The occurrence of gold with bismuthinite and bismuth telluride in contact zones was not attributed to recrystallization of the limestone, as inferred by Professor Kemp (page 604), but to the infiltration phase of metamorphism. On page 604 also Professor Kemp states:

> "The great masses of magnetite and specular hematite, which we so often meet in the zones, are indeed attributed to introductions from the eruptive, but the introduction of silica, alumina, and the iron oxides of the silicates is opposed."

This is hardly a just inference. That silica, alumina, and the iron oxides may belong to both periods of formation was clearly stated in my paper.

On page 605 Professor Kemp cites a "fundamental error," in my paper, which he says seems unanswerable. This is with respect to the elimination of calcium and magnesium carbonates, and the retention of silica in its most soluble form of chert. Whether lime and magnesium carbonates are carried away in solution in alkaline waters, or whether they are eliminated like the water in shales under conditions of dynamic metamorphism, or like silica when a quartzite is converted to a sericite schist, is not known. It seems established, however, that they are at least partly eliminated under any hypothesis. No other proof of this

is necessary than the case cited by Professor Lindgren for the Morenci district, where limestone has been changed to garnet without noteworthy change of volume. Retention of all the calcium and magnesium in the secondary silicate zone would demand an increase of volume over that of the original limestone. This is hardly compatible with conditions of igneous intrusion. It is generally assumed that substances introduced into the contact zone from the magma find room in part by replacement, which involves elimination of lime and magnesia. Why not, then, elimination in some cases without replacement? How these carbonates were carried away is a question out of the realm of this discussion. However, as shown by Barrell,[1] Leith and Harder,[2] Brögger, and Lindgren,[3] contact deposits frequently form in the zone of fracture, at depths ranging from 1,000 feet to 5,000 feet, and under such conditions avenues of escape for excess constituents are numerous.

Professor Kemp, on the same page, states that it is extraordinary that magmatic waters highly charged with carbonates should not dissolve and carry away silica, iron, and alumina, especially when the silica is in its most soluble form of chert. To quote a sentence:

> "Some of the generally trusted chemical views of the Lake Superior geologists upon the rearrangements of silica and iron oxides in the cherty iron carbonates of Michigan and Minnesota must be very faulty if Mr. Uglow's ratios are to be trusted as casting light upon the problem."

The two cases cited by Professor Kemp are scarcely comparable. It is hardly to be expected that elimination of substances under conditions of weathering as in the Lake Superior district, and of contact metamorphism would take place by exactly similar methods or processes. Even if the two cases were comparable, the difference in results should be readily explained on the principle of relative solubility. No doubt, the waters, which are inferred by Professor Kemp to carry away the lime and magnesia, would also dissolve some silica, but they would

[1] Prof. Paper No. 57, U. S. Geol. Survey, 1907.
[2] Bulletin No. 338, U. S. Geol. Survey, 1908.
[3] Prof. Paper No. 68, U. S. Geol. Survey, 1910, p. 41.

dissolve the carbonates at such a relatively greater rate that the silica would remain practically unchanged. In the case of the Lake Superior iron formation, on the other hand, solution has proceeded much farther, and besides having removed the carbonates, has locally in the ores eliminated considerable silica which is more soluble than alumina and iron oxide. In the great mass of the formation, for example, the jaspilites and ferruginous cherts, the silica has remained undissolved, and the iron-silica ratio is essentially the same as in the original unaltered cherty iron carbonates. However, in accordance with the hypothesis under consideration here, the elimination of the lime and magnesia is not attributed to the work of magnatic waters, but may be accomplished by a method similar to the squeezing out of excess constituents under conditions of dynamic metamorphism. This elimination probably takes place during the first phase of the metamorphism, and therefore before any important emission of gases or solvents from the magma.

On pages 605 and 606, Professor Kemp states:

> "Garnets contain between 30 and 40 per cent. CaO; vesuvianite the same; diopside between 40 and 50 per cent. CaO and MgO; wollastonite 40 per cent. CaO; and other common silicates similar percentages. A pure limestone has only 56 per cent. CaO, and a pure dolomite about 52 per cent. CaO and MgO. Thus while solution by magmatic waters is removing something like 10 to 20 of the 40 to 50 or more per cents. (that is one fifth to two fifths) of the CaO and MgO in the limestones, it must at the same time increase the silica, alumina, or iron oxides up to 3 to 10 times their original amounts. No such process seems conceivable."

If silica is considered to remain constant, its original ratio to lime (say 1:54) in the limestone, may be changed to any larger ratio (say 40:35) in a combination of the above mentioned silicates, by the elimination of all the carbon dioxide and a considerable portion of the lime from the limestone. Viewed in this way the process seems perfectly conceivable.

The writer regrets that at the present time he is unable to take up more in detail some of the literature on contact metamorphism, but feels that the above explanation should help to clear up any misunderstanding of his position.

W. L. Uglow.

FIELD AND OFFICE METHODS IN THE PREPARATION OF GEOLOGIC REPORTS.

SOME PRINCIPLES UNDERLYING GEOLOGIC MAPPING.

Sir: The principles underlying good geologic mapping are stated more easily perhaps if one assumes the possession of a good base map—a topographic contour map if possible. Differences in base maps—in accuracy, scale, and consistency—and the effect of such differences on geologic mapping—need not be considered, for this effect will not greatly alter the principles involved.

Inasmuch as good geologic mapping is intimately dependent on good geologic investigation, a consideration of the problems connected with geologic investigation should determine in part the problems of geologic mapping. Very briefly stated, geologic field investigation has for an end the determination of the areal extent and the interrelation in space of particular elements of the earth's crust. The word particular is used because these parts are not arbitrarily selected but are chosen in relation to three primary groups of geologic facts: facts relating to stratified rocks, facts relating to igneous rocks, and facts relating to structure. A geologic map then will show the areal extent of stratigraphic units, the presence or absence within these units of igneous rocks, and their attitude and concordant or discordant relation among themselves. Stated more concisely, all the varied items connected with stratigraphy, all the types of intrusion and their metamorphic effects, all the complicated structures of folding and faulting are features which can be represented cartographically. This threefold grouping of geologic elements, viz., stratigraphy, intrusion, and structure, is fundamental from the standpoint of visualizing earth structure.

If the geometric relations of these elements are examined it is evident at once that a concept of *three dimensions* is involved; for example, sedimentary formations[1] are tabular in form, their areal extent is great compared with their thickness. Normally, their surfaces (top and bottom) are essentially planes and within limited areas commonly approximately parallel planes. These planes

[1] For the present the subjects of lateral gradation, unconformity, overlap, etc., are neglected.

intersect the surface of the earth in lines, which are the geologic boundaries—the lines which are to be represented upon the map. Obviously the configuration of the boundary lines is controlled by geometric laws. For example, if the unwarped plane surface at the base of a formation dips in any given direction, the intersection of this plane surface with the surface of a diverse topography (that is, the boundary line) will have characteristics expressing this fact. Such a boundary in crossing a stream valley oblique to the strike will be first deflected from, and then recurve into its general course. The mode of this jog, that is, the point of

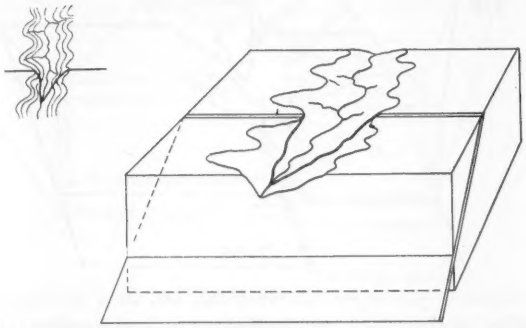


FIG. 74.

greatest deflection in the boundary line (see Fig. 74) must be placed exactly in the stream and not on the side of the valley wall (see Fig. 75). This is fixed by geometric considerations. In the first case the boundaries are the normal ones that would be formed by such a plane surface as is postulated intersecting a valley wall, while in the second case the boundaries are those of a warped surface—not postulated—intersecting the same valley wall.

With this concrete case as an illustration it is apparent that the various boundaries of sedimentary formations in a folded region are dependent for their position upon geometric laws, laws having to do with the intersection of planes or warped surfaces.

The accurate tracing and representation of such contacts reveals the nature of the folds and here must be emphasized the reciprocal functions of mapping and investigation, *i. e.*, accurate mapping

leads to an understanding of structure; an understanding of structure leads to accurate mapping.

If now this geometric viewpoint be carried into the field of faulting another concept is introduced—that of discontinuity. Where, in the first case, we imagined the existence of an unbroken plane we must now think of such a plane interrupted and inter-

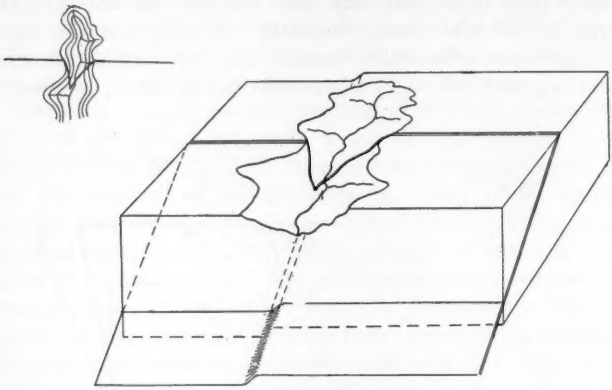


FIG. 75.

sected by another plane, the fault plane or fault surface. Where boundary lines encounter this vertical plane, they are cut off (see Fig. 76). Nevertheless, there may be and generally is, within the area on the opposite side of this fault plane, a continuation of the boundary. The position of this continuation on the surface will depend on several factors, but the point to be emphasized is that the three-dimension conception is always necessary and useful and that sedimentary contacts must be geometrically accounted for.

The spacial relations of igneous bodies are normally different from those of stratified formations[1]—the form of their limiting surfaces is irregular and has no foreseeable geometric relation to the surface of the earth. The intersection of two irregular surfaces therefore combine to form its contact, a contact unpredictable by any geometric law and subject only to determination by

[1] Intrusive sheets and lava flows have some important similarities in form to sedimentary rocks.

observation. Igneous boundaries have in general the quality that they must close—they have but *one* boundary, an almost too obvious statement some may say perhaps, nevertheless a useful concept in the field and one which has been disregarded, *i. e.*, open contacts grace or disgrace certain maps.

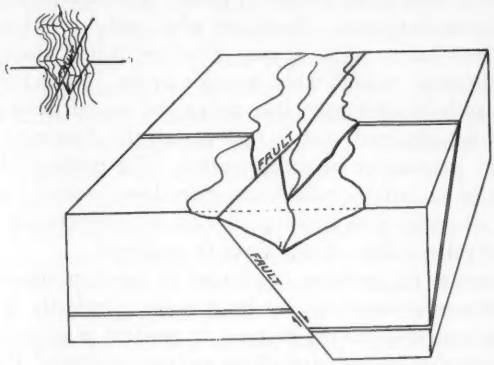


FIG. 76.

To epitomize what has just been said regarding geologic concepts. It is the space or three-dimension conception of geologic units which lends itself best to an appreciation of geologic structure. It is the geometric relations of sedimentary rocks which are important, and the lack of predictable geometric relations in igneous rocks which should be kept in mind while mapping, and finally the understanding that geologic observation and geologic record are mutually necessary to clear geologic interpretation.

Certain precepts underlie the best practice in that part of geologic mapping which involves the actual delineation of boundaries on a map. The first is that of precision; the second hinges on the idea that the best record is that obtained at the time of observation. Precision is a matter of location. Location is a matter of scale and method. All locations should be accurate up to the scale of the map and the method employed in mapping, by which is meant that on a contour map a located point should fall between

the contours of the map indicated by some method of obtaining elevations, barometers, hand level, etc., and should be a definite distance from a point determined by pacing, stadia, or taping, in a direction determined by compass or transit. The point of a sharp pencil is the only arbiter of what can or can not be expressed.

A line is made up of a series of points. Obviously one can not determine all the points. Therefore select useful points in determining boundaries, points of easy reference, points which can be easily found or checked when occasion arises. Some points are more readily located than other points and are of more general utility when obtained, that is, they permit the drawing of more boundary per number of points located. The position of points on boundaries in their relations to ridge lines, stream junctions, summit of peaks, road crossing, etc., are all determinable and of practical value. They should never be neglected.

The matter of precision is affected by cover or obscurity or indefiniteness of boundary, not by geologic complexity or relief. When a boundary can not be seen, its position is estimated and located after the weighing of all the geologic evidence. Precision here therefore gives way to approximation. The factors underlying a judicious estimate of the location of an obscure boundary are many and will not be discussed at this time, but it may be said in general that while the errors arising from necessary approximations may be passed over, inaccuracy on a good topographic map, where the geologic fact is ascertainable, is not so excusable.

There is one procedure which is so useful and important and yet perhaps so often neglected that it will be mentioned here. It concerns the matter of actually tracing boundaries. Most boundaries should be traced. There are conditions such as those presented by flat-lying or gently-dipping unwarped sedimentary strata where a method of connecting up a series of accurately located points is the most expeditious, practical, and economical course to pursue; but in all other cases grave errors of location and oversight of important geologic relations is apt to creep in if such a method is followed.[1] By tracing a boundary is meant the

[1] Detailed observations are often possible at points on contacts where least expected. Contacts in case of sedimentary rocks as well as of igneous rocks

actual following of the contact (as nearly as is convenient and expedient) and the accurate location of a number of points so closely related that no chance for error or oversight is possible, taking into consideration, of course, the scale of the map employed. This idea of continuity, of actual assurance that a contact is just here and not there, that a certain bed is connected throughout an area and is distinct from another bed very similar perhaps in appearance is very important. Upon it hinges the correct determination of structure in a region and the practical value of the map. The more complicated the geology the more necessary it is actually to trace formation boundaries. In areas of pre-Cambrian rock the need is almost imperative.

The second rule for good practice, that first-hand record is the best, is quite as important as that of precise location. In every field of enquiry first-hand information is the best. If a contact can not be located in the field it cannot be located in the office. If a guess is necessary, the guess is best made on the ground. It being impractical to carry around a map covering an entire area and it being undesirable to subject a final map to the vicissitudes of dirt and weather, the best practice lies in *accurate location in the field* on sectional maps and a compilation of such information at short intervals. With a record kept up to date the status of the work is always known, and one problem may be settled before a new one is taken up or camp moved beyond easy reach of the critical locality. The work can be planned with a clear idea of what has been accomplished and what remains to be done. A striking result is that the geologist does not so often wish that he could go back just for one day in order to fill in a sorry gap.

Summary.—In bare outline it may be said that the principles underlying good geologic mapping rest on, first, a clear conception of the spacial element in geologic structure:—the concept of three dimensions as applied to formations; second, on an appreciation of the importance of precision, and third, on a belief in the value of first-hand completed record. SIDNEY PAIGE.

are where things have happened and therefore they are strategic points for attacking problems.

REVIEWS

Economic Geology. By CHARLES H. RICHARDSON. McGraw-Hill Book Company, Inc., New York. 1913. Price $2.50.

In his preface, the author of this 320-page text-book states that the publication is based on a series of lectures which he has been compiling for more than 20 years. The work then should be no crude effort, no mere hasty throwing together of second-hand data; but, on the contrary, ought to set forth the essentials of economic geology with some originality of thought and method, with some indications of an intimate knowledge of the subject treated, and, especially, with some evident realization of the responsibility that rests upon a teacher to think clearly, to express himself accurately, and to present his material in the effective orderly way that should come from ripe experience in teaching. In all of these respects the book is disappointing.

At the outset, the author's title is misleading; for only the metalliferous deposits are considered and no attention is given to the geology of coal, oil, phosphates, saline deposits, clays, underground water, etc., or to the relation of geology to engineering construction.

A very large proportion of the material, including most of the illustrations, has been taken, with scrupulous acknowledgment, from two or three elementary text-books and neither texts nor illustrations have gained by the transfer. The repeated citation of two or three compilers as authorities on districts and deposits which they have never studied and, in some instances, have not even visited, is ridiculous to geologists cognizant of the facts. Moreover, in the comparatively few cases where the author has attempted to go to original sources of information he has shown little critical judgment, has not availed himself of the latest published data, or has garbled his authority, as in the absurd account of the origin of the ores in the San Juan region, Colorado, given on page 69.

The complete absence of all bibliographic references is explained by the author as intentional, he, for some inscrutable reason, deeming it better for each teacher to supply references to his students.

Examples of loose thinking and consequently of slipshod expression may be found on almost every page. The following are a few culled at random:

"The ores of cadmium are not confined to any particular geological horizon. They are, in fact, the same as *that*[1] of zinc" (page 162).

[1] Italics in all quotations are the reviewer's.

"In the broadest sense a *mine* may be said *to consist of a body of ore* sufficiently large and rich to pay for the original purchase price of the property, all costs of mining, transportation, reduction plant, together with a large percentage of interest on the investment" (p. 20).

"To the geologist the altered walls of the lode and the minerals of the lode *determine* the character of the magma from which the ore was derived" (p. 30).

When their instructors think and write in this fashion it is little wonder that the young men of our universities should so often be careless or oblivious not only of the capacity of our language to convey to others the thoughts that are in us, but of its latent power of retaliation in exposing the mental obfuscation of those who abuse it.

The author apparently has no clear conception of what is meant by metasomatism or metasomatic deposits, and his treatment of contact-metamorphic deposits is very inadequate.

Erroneous statements of fact abound, as for example:

"In Idaho *at Coeur d' Alene* the ore galenite is found with siderite gangue in highly folded quartzites and *mica schist*" (p. 95).

"*Native* lead *occurs* in small quantities *in many localities* both in the United States and in foreign countries. It is always of secondary origin, the product of reduction from other lead minerals through *volcanic* action" (p. 110).

Under the heading *New Mexico* (p. 96) appears the surprising information:

"In Wardner *County* and Bitter Root *Mountain*, Idaho, galenite occurs in quartzite and *mica schist* in large *chutes impregnating* the fissured hanging walls. This is one of the most productive regions of the world."

Then follow, still under *New Mexico*, notes on the *Thames* district (New Zealand?), on the *Freiberg* district (Germany?) and on *Japan*. Cordillera and its adjective are used throughout as if they referred to a part only of the Rocky Mountains, instead of to the whole mountain complex between the Great Plains and the Pacific.

Proof-reading apparently was considered by author and publisher as an unnecessary refinement and, among the many typographic blunders, perhaps the least pardonable is the consistent misspelling of the name of America's most distinguished living geologist. The volume reflects as little credit on its publishers as it does on its author.

Severe condemnation of a work which undoubtedly represents considerable labor in preparation is never an agreeable duty. The circumstances which in this case impel plain words are: the book is evidently intended chiefly for young students of economic geology; it has been written by an experienced teacher in a reputable university, who contemplates a companion volume on the non-metalliferous deposits; and it

is published by a firm with so many excellent volumes to its credit as to make its acceptance of this particular manuscript little short of amazing.

F. L. RANSOME.

Mineral Deposits. By WALDEMAR LINDGREN. McGraw-Hill Book Company, Inc. 1913.

Ever since the announcement of Lindgren's "Mineral Deposits," students of ore deposits have been awaiting its appearance with more interest than usually attaches to the publication of a new book. This interest is due to the high standing of the author and to the fact that this is the first extensive American treatise on the subject.

"Mineral Deposits" is an orderly summary of the writer's ideas regarding the origin and interaction of the varied processes of ore deposition and contains terse and often novel analyses of each group of deposits classified according to the dominant process by which it was formed. The reviewer has found so much that stimulates and is of interest in reviewing the whole subject of mineral deposits from the view point of Mr. Lindgren, that it seems worth while to give at least the gist of his broad summary conclusions, to emphasize whatever appears to be novel, as well as to call attention to certain phases of the science that have received inadequate treatment or have been omitted entirely.

As indicated by the title, Mr. Lindgren treats both metallic and non-metallic substances, with the exception of hydrocarbons and structural materials. He covers this broad field, because all mineral deposits are the result of geological processes, and find places in his classification. The volume's limit in size (doubtless due to commercial reasons), and the insertion of the material upon non-metallic substances has forced the omission of a number of important subjects belonging to ore deposits, such as the description of the metallogenetic epochs and the delimiting of the metallogenetic provinces especially of the United States. Mr. Lindgren has described the former elsewhere[1] but De Launay's[2] masterly work on the metallogenetic provinces of the eastern hemisphere could be completed by no one as well as by Mr. Lindgren.

This lack of space has forced undue condensation of the descriptive summaries, and inadequate treatment of certain relations of ore deposition to the dynamic history and structure of the region in which they occur.

The scope of the book is stated as follows: It "will be confined to a description, by classes and type examples, of the occurrence, structure and origin of the principal deposits of metallic and non-metallic sub-

[1] "Metallogenetic Epochs," ECON. GEOL., Vol. 4, pp. 409–420 (1909).

[2] Latest summary in *Traité de Métallogénie*, Vol. 1, pp. 241–288.

stances." The foundation, however, on which the book is built, and the dominant note throughout, is paragenesis in the broader sense, the determination of the groups of minerals, and therefore the types of ore deposits produced at different temperatures and pressures. Physical chemistry is emphasized, and since temperature is more important than pressure in the determination of chemical equilibria, the former is the important factor in determining the group of minerals of an ore body. The classification according to both temperature and pressure leads to some difficulty because high temperatures may occur at moderate or even slight depths, and further, the successive phases of a single family of ore deposits may grade from the high temperature deposits formed at or after an intrusion to lower temperature veins of a later phase, and yet all at about the same depth.

The determination of the limits of temperature and pressure under which each type of ore deposit is formed, is one of the valuable features of the book, and this has been made possible only recently, by the careful geological study of ore deposits, resulting in the determination of the thickness of strata that have been removed since ore deposition, and the construction of a "geological thermometer" by the geochemists. This data gives a rational basis for the discussion of "the permanence of ore deposition with depth," which has occupied so much space in American scientific and mining journals.

The thesis that mineral groups formed by ore deposition and concomitant rock alteration vary with temperature and pressure, has led Mr. Lindgren to describe these groups with care, and this work has been done more carefully and thoroughly than elsewhere in literature.

The book falls into three parts. The first part of twelve chapters is introductory, and discusses ore forming processes, the structure and texture of ore deposits, and related and modifying geological phenomena. Part two (Chapter 13) includes a discussion of earlier classifications, and an exposition of the one adopted by the writer. Part three (Chapters 14–30) is a description of all mineral deposits (except fuels and structural materials), classified according to the principles outlined in chapter thirteen.

The first chapter is a summary of the distribution of the elements, and especially the traces of metals in the earth's crust, and short as this discussion is, it has added much to our knowledge of the subject, modifying to some extent the conclusions reached by Vogt[1] in his elaborate investigations of this subject.

Chapter two is a far too brief summary of physical chemical principles. The important factor in ore precipitation, viz., the change in

[1] For summary and references see "Die Lagerstätten der nutzbaren Mineralien und Gesteine," Beyschlag, Krusch-Vogt, Vol. I., pp. 126–148.

equilibria due to loss of volatile mineralizers (H_2S, CO_2, etc.), receives scant notice.

The chapters on the flow, composition and chemical work of the underground waters, are not only good summaries of the subject, but also contain a contribution to science, in the conclusion that, while the composition of the circulating waters of the sedimentary rocks shows a direct relation to the kind of rock they traverse, this is not the case in certain hot springs in igneous rocks containing chlorine, bromine, fluorine, etc., as well as some containing large amounts of H_2S and CO_2.

The treatment of metamorphism is broad and satisfactory. Van Hise's and Grubenmann's concepts as to the effect of temperature and pressure are made more exact, and the differences are explained between ordinary metamorphism and that accompanying ore deposition. An important list is given of the mineralogical characteristics of the three great groups of ore deposits genetically related to igneous rocks: high temperature and pressure deposits, intermediate temperature and pressure deposits, and moderate temperature and pressure deposits. Tourmaline is given as a high temperature and pressure deposit. It has been found, however, in altered rhyolitic and andesitic rocks of Arizona and Mexico, and may occur as a high temperature mineral under intermediate or even moderate pressures.

Folding and faulting are discussed briefly, the treatment of the latter following the report of the committee of the Geological Society of America on the nomenclature of faults. The discussion of rock openings, form, structure and texture of ore deposits is probably the best that could be written in the space devoted to the subject. The chapter on ore shoots is more descriptive than analytical.

The key to the descriptive portion of the book is found in the classifications of mineral deposits adopted by Mr. Lindgren. It is also important since it contains his conclusions as to the temperature and pressure under which each type of ore deposit is formed.

In the descriptive portion of the book, each main group of deposits is treated under a separate chapter with appropriate heads. Important deposits and conclusions appearing under each are summarized in the following:

"Deposits Formed by Mechanical Processes of Transportation and Concentration." Here are included (1) pure quartz sand, (2) placer deposits of gold, platinum, cassiterite, monazite, and minor materials. The discussion of gold placers is more nearly complete than that of most other topics discussed, and shows in its general excellence the wide experience of the author in this class of deposits.

The gold bearing conglomerates of the Transvaal are included here, and although many will agree with the author that "their correct place

in the genetic classification is as yet uncertain," the reviewer believes that the data now available suggest a strong probability that the gold was introduced by solutions under conditions of intermediate temperature and pressure and in genetic relation to igneous rocks.

"Deposits Produced by Chemical Processes in Bodies of Surface Water by Reactions between Solutions." Here are grouped such various deposits as chalk, all varieties of limestone, dolomite, chert, and diatomaceous earth, sedimentary sulphide deposits, sedimentary iron and manganese ores, and sedimentary phosphate beds.

In regard to sedimentary sulphide deposits, the author concludes that "there is little evidence of extensive sedimentary beds of pyrite" and "still less evidence as to the sedimentary deposition on a large scale of sulphides other than pyrite or marcasite." Under sedimentary iron ores are included black-band ore and bog iron ore; oolitic siderites, limonites, hematites, and silicates. The author summarizes the various ideas as to the origin of these tremendously important iron deposits and the difficulties of thoroughly explaining their complex history. He concludes that "limonite and glauconite are actual sedimentary products" (deposited in shallow water) and "siderite may form in the presence of much organic matter" while "the chemical precipitation of hematite on a large scale has not been observed."

The phosphates are considered very briefly, and the mineralogical discussion is incomplete even for a condensed account.

Saline residues are briefly treated under two types: "the oceanic type of waters" yielding "deposits of gypsum, common salt, and finally potassium and magnesium salts, and the volcanic type yielding soda, glauber salt, borates, probably nitrates as well as more or less sodium chloride." Mr. Lindgren describes the wonderful salt domes of the coastal region of Louisiana and Texas and suggests as an important factor in their formation, the "extraordinary plasticity of rock salt which yields far more easily to pressure than the surrounding rocks."

Under "Mineral Deposits Resulting from Processes of Rock Decay and Weathering," appears an excellent summary of the mineral changes developed by these processes, and descriptions of deposits of clay, residuary iron ores and ochers, manganese ores, residuary zinc ores of Virginia and Tennessee, residuary phosphates, hydrated nickel silicates and bauxite. The treatment of the last mentioned is incomplete, especially the discussion of its genesis. Mr. Lindgren recognizes that decomposition of rocks under tropical conditions may produce hydrates of alumina instead of clay, and the generalization is ventured that most of the deposits of bauxite were simply the results of weathering in place under tropical or semi-tropical conditions, but without the aid of especially acid or alkaline solutions. Such a simple generalization neglects impor-

tant modifying factors, such as the fact that certain basic rocks decompose more easily into aluminum hydrates than other kinds of rocks, and this decomposition may take place under other climates than tropical; and further that undoubtedly bauxite has been formed by the action of sulphuric acid in certain localities (New Mexico and Arizona). An interesting occurrence was brought to the reviewer's attention by Mr. R. H. Forbes, which may help us understand how some of the larger bauxite deposits are formed. A deposit of rather pure bauxite was formed at the junction of two trickling streams, one of which was charged with aluminum sulphate, probably resulting from the oxidation of a pyritized tuff, and the second carrying much sodium carbonate, as is common in arid regions.

Under the next head "Deposits Formed by the Concentration of Substances Contained in the Surrounding Rock, by Means of Circulating Waters," some geologists would include most mineral deposits. Mr. Lindgren's point of view is well summarized as follows:

"In a rough way the deposits resulting from the work of underground waters of meteoric origin may be divided into (1) those formed from abundant material contained in the surrounding rocks, for instance, magnesite, serpentine, sulphur (by reduction of gypsum), and certain kinds of hematite; and (2) those formed by the deposition of rarer substances dissolved by the water from the surrounding rocks or from rocks that lie deeper. In this second division it is possible to indicate with great confidence the derivation of some substances—*e. g.*, barite from certain limestones, and copper from certain basic igneous rocks; but the exact derivation of some other substances may be doubtful.

"Waters of atmospheric origin doubtless have the power to dissolve many of the rarer metals contained in rocks, to carry them for considerable distances, and to concentrate them in places suitable for deposition; but unless it is aided by higher temperatures at considerable depths below the surface this power is probably not strong enough to produce important deposits of these rarer metals."

The treatment of sulphur is incomplete. Regarding its genesis, the deposits of "volcanic" and hot spring sulphur are recognized as the result of incomplete oxidation of H_2S at the surface. Regarding "sedimentary sulphur" however, Mr. Lindgren concludes that it must be derived from gypsum, simply because of the close association of sulphur with that mineral. His explanation is not acceptable that gypsum produces H_2S by reduction, and the sulphur is formed, at depth, in the absence of oxygen, by the reaction of the H_2S on $CaCo_3$; because So_2, or hyposulphites are needed to cause this reaction.

Since gypsum is in general a product of evaporation in arid regions, and since in such hot evaporating lakes, the bacterial production of sul-

phur takes place (as is strongly suggested especially by MacDougal's observations on the Salton sea), and since, moreover, in such a situation H_2S may be evolved from a number of sources, and a partial oxidation of this produces sulphur, it appears to the reviewer therefore that sulphur, the natural associate of gypsum, is probably formed at the same time as the latter and not from it. Concentration of this disseminated sulphur, by solution and reprecipitation, deep below the surface, may take place as follows: Sulphur is readily soluble in alkaline solutions, especially as calcium polysulphide, and a precipitation of the calcium as calcium carbonate would be accompanied by the evolution of H_2S and the precipitation of sulphur. Such an origin is suggested by the phenomena described to me by Mr. R. W. Moore, who was engaged in drilling the sulphur deposits of Bryan Heights, Texas. Artesian brine water charged with lime, CO_2 and H_2S was tapped on reaching the sulphur deposits. On standing, the sulphur precipitated rapidly from the yellow solution, and this precipitation may be greatly accelerated by addition of acid.

The occurrence of the sulphur furnishes additional evidence of an epigenetic origin. It occurs in masses and veinlets concentrated under and in a porous "cap limestone," decreasing in amount in the underlying gypsum in which it occurs as veinlets accompanied by calcite.

A further possibility as to the origin of sulphur, that does not seem to have been emphasized in literature, is suggested by the work of Stokes[1] on the decomposition of pyrite by alkaline solutions, and the formation of alkaline hyposulphites and polysulphides. These of course would easily form the lime polysulphide and would precipitate as suggested above.

Mr. Lindgren's summary concerning the hematite deposits of the Lake Superior district is chiefly interesting on account of the emphasis laid upon some of the unsolved problems regarding their genesis. He notes that the ores were largely concentrated during pre-Cambrian times, that the present ground water does not dissolve and precipitate iron, and that, on account of the present high water level, it is unable to produce the extensive oxidation shown in the ore bodies. He believes "that hematites appear to result from the oxidation in arid and tropical countries" and that probably an arid period existed in pre-Potsdam times. In his description of the residual iron ores of Cuba he points out similarities between these rich hematite ores and the Lake Superior deposits, and bearing in mind the hypothesis he advanced for the sedimentary iron ors, the reader has little difficulty in framing the alternate hypotheses hinted at, namely that residual hematite caps were formed during arid pre-Potsdam periods; that these were transported and deposited, chemically and mechanically, as a part of the several "iron formations," and

[1] ECON. GEOL., Vol. 2, pp. 14–23 (1907).

that later, but still in pre-Potsdam arid times, concentration and complete oxidation of the troughlike bodies occurred.

Mr. Lindgren's views regarding the ores of copper, lead, uranium, vanadium, etc., in sandstone and shale have been made public previously, and he emphasizes here again that the copper deposits of this class are formed on the flanks of older continental land masses, from which the copper has been removed and deposited along the margin by mechanical and chemical agencies, the transporting solutions containing sodium chloride and calcium sulphate, and the climate arid.

In regard to the most important example of this class, the Mansfield copper deposit, Mr. Lindgren states that "the Mansfield basin was simply, then, the final collecting place of the solutions from the adjacent desert shores."

The probable formation of certain veins in the saline Paleozoic and Mesozoic beds of central Germany, and the formation of certain veins carrying hematite, barite, etc., by inter-Permian brines are further examples of the relations of aridity to ore deposition.

One cannot but regret that the description of the remarkable vanadium deposit near Quisque, Peru, consists of but a short paragraph on its mineral composition, when so many interesting data are available in the descriptions of Hewett and Hillebrand.

Among the deposits that are believed to have been "*concentrated by meteoric circulation at moderate temperatures and slight depths, not connected with igneous processes,*" are the copper sulphide deposits in basic lavas including the Bonanza chalcocite deposits of the Copper river district, Alaska, and the Foothill copper belt deposits of California in greenstone. There will be considerable dissent from the conclusions regarding both of these, and we lack sufficient field and microscopic data as yet to reach any satisfactory conclusions.

A chapter is devoted to "Deposits Resulting from Regional Metamorphism." Many European deposits show the effect of regional metamorphism which masks their origin, and they have given rise to endless discussion by foreign geologists. Mr. Lindgren concludes that deposits resulting from regional metamorphism are probably unimportant, but that deposits of various kinds may be rearranged by this process and "it is hopeless to speculate on the subject until the metamorphic series at the location of typical fahlbands has been more carefully examined as to the original character of the rocks."

The chapter on "Deposits of Native Copper with Zeolites in Basic Lavas" is interesting because native copper in amygdules of basic lavas is a world-wide distributed type, although the only example of great economic value is the Lake Superior deposits. Knopf is corroborated in his statement that "any theory accounting satisfactorily for the zeolites

will also account for the copper." Mr. Lindgren summarizes the data suggesting that zeolitization and the deposition of native copper are caused by the attack of descending salt solutions on the still hot lavas. He suggests the reaction of hot sea water on submarine lava flows, but possibly the salt waters are connected with arid climates, especially that of the Keweenawan period.

"Lead and Zinc Deposits in Sedimentary Rocks. Origin Independent of Igneous Activity." Mr. Lindgren emphasizes that we have to do with a type of world wide distribution, of a simple mineral combination suggesting a very moderate temperature, and with no apparent connection with igneous rocks. The ores are concentrated by either descending solutions or ascending artesian circulations, and he suggests that chloride solutions mixed with sulphates were the transporting agents. Later he mentions Siebenthal's important observations that the deep artesian waters of Missouri, Oklahoma and Kansas contain in solution much iron sulphide as well as sulphides of zinc, lead, and copper. They also contain salt and hydrogen sulphide ór are alkaline waters with earthy carbonates. May it not be therefore that the lead and zinc which are concentrated from the Paleozoic strata of the Mississippi valley, are carried as sulphides in the presence of hydrogen sulphide and carbon dioxide in much the same manner, from the chemical standpoint, as the ores of the deeper seated vein deposits?

The remaining chapters deal with deposits which the majority of economic geologists admit are closely related to igneous rocks. As the author has been one of the investigators who has been most active in gathering the geological and mineralogical data that demonstrate this idea, and as his diligence in publishing his data and his conclusions has made the same well known, the reviewer purposes to summarize chiefly what seems to be new, and to suggest points regarding which he differs somewhat with the author, and is compelled, therefore, to pass over the most valuable and interesting part of the book with but little comment.

The treatment of "Those Metalliferous Deposits Formed near the Surface and Closely Related to Extrusive Vulcanism" is the best of the volume, and the summary of rock alterations, mineralogical characteristics, structures and textures of the ores is especially satisfactory.

The author champions the idea, first emphasized by Spurr, that the extrusion of metallizing waters is an intervolcanic episode, and that there may be several of these episodes, the ore-forming waters of which may be of strikingly different character. The description of the various individual deposits is chiefly mineralogical. Their structural features and general geological relations receive little notice, nor is there any discussion of the great metallogenetic provinces to which this type of ore bodies belongs.

The description of the Tonopah mines is founded on Spurr's earlier work, and no notice is given to his later exhaustive investigations, the results of which modify his earlier conclusions.

The chapter describing deposits formed at intermediate temperatures and pressure includes the majority of ore bodies. All veins and replacements which are not accompanied by what are considered high temperature minerals are grouped here. This arrangement has the disadvantage of breaking into the ordered sequence followed by oreforming processes especially around small intrusive centers where contact deposits are often followed by high temperature deposits, these going over by gradation into intermediate temperature deposits. These rapid changes are most pronounced in deposits formed in and around small monzonitic intrusives and especially well shown in certain Mexican occurrences described by Spurr[1] and Bergeat;[2] and from information furnished the reviewer by Mr. Basil Prescott, the change from low temperature to high temperature mineral groups, as well as to those described as resulting from igneous metamorphism, occurs in a single vein with increasing depth.

The separation of deposits according to this grouping also breaks with the concept of metallogenetic provinces. For instance, the Sierra Nevada-Alaska province of gold quartz veins is one of the most definite known. The veins were all formed after the intrusion of the Sierra Nevada batholith, as a definite system along its margin, and the fissures were probably developed within one great dynamic epoch. They are remarkably similar in composition and mineralogy, and yet because the gold quartz veins of Alaska show perhaps a greater tendency to develop high temperature minerals, and were possibly formed at somewhat greater depths, they are classified as a separate group of deposits.

Under high temperature deposits the distinction often emphasized between pneumatolytic veins and other high temperature veins where the action of strong mineralizers such as fluorine, boron, etc., is not evident, is abandoned. In discussing the mineralogy of these deposits, the author insists that kaolin, including its crystalline variety nacrite, is never a high temperature mineral but is always a product of alteration by descending waters. This conclusion may well be considered as an expression of his personal opinion and lacks proof.

Under the heading "Deposits Formed by Processes of Igneous Metamorphism" are included the well-known "contact deposits," the mineralogy and genesis of which are excellently discussed, and the well-known view of the author is emphasized that there is a great transfer of mineral substance from the magma into the adjacent rock.

[1] "Ore Deposits of the Velardena Dist., Mexico," ECON. GEOL., Vol. III., pp. 688–725; "Study of a Contact Metamorphic Ore Deposit," ECON. GEOL., Vol. VII., pp. 444–493.

[2] Inst. Geol. de Mex. Bull. 27 (1910).

In addition to metallic substances, garnet and graphite are included here. Although the latter is classified as an igneous metamorphic mineral, the following occurrences are recognized: (1) As an original mineral of igneous rocks. (2) As a mineral of pegmatites. (3) As a regional and contact metamorphic mineral. (4) As a vein mineral.

In regard to the genesis of graphite, especially as a vein and pegmatite mineral, no mention is made of the suggestion of Winchell that water vapor at high temperatures attacks carbon, producing carbon dioxide and hydrogen by reversible reaction, and at lower temperatures (below 500° C.), the hydrogen may react on the carbon dioxide to produce crystallized carbon, unless the hydrogen parts company with the carbon dioxide before the temperature is lowered, which may often happen on account of its greater mobility, or by intervention of any chemical reaction fixing either one of these. It is possible that this explanation may throw some light on the formation of the diamond, notwithstanding the general acceptance that the mineral is a "dry melt" product of basic igneous rocks.

The heading "Deposits Due to Igneous Metamorphism, not Distinctly Related to Contacts" proves a rather necessary catchall for the varied deposits accompanied by metamorphic minerals, the genesis of which is in doubt.

The discussion of "Minerals of Pegmatite Dikes" is interesting not only as a good summary of the occurrence of certain gem minerals but also of the conditions under which pegmatites form, of the action of mineralizers, and of their relations to ore deposits.

The discussion of "Mineral Deposits Formed by Magmatic Differentiation" is brief, and contains little new data. The author recognizes the fact that sulphides formed in this way are invariably later than the silicates, and it appears to the reviewer that this important conclusion is a noteworthy departure from the view that magmatic segregations are accumulations of the minerals that crystallize during the early stages of the congelation of the magma. Under the latter idea there is a hiatus between the magmatic sulphide veins and the high temperature veins. Under the former, if the sulphides crystallize at a late stage, they are probably accompanied by vapors and mineralizers, and a continuation of the process may carry these deposits over into high temperature veins. Mr. Lindgren agrees with those investigators who, while recognizing that these sulphides are later than the rock minerals, have interpretated the lack of hydrothermal metamorphism in connection with the ores as proof that they belong to the "magmatic period." Possibly, however, at the high temperatures, obtaining shortly after the consolidation of the basic rocks, the ore forming solutions are in equilibrium with the rock minerals, and therefore do not break them down while introducing the

ores. If magmatic sulphides grade into ore veins, the controversy that has arisen over these puzzling occurrences is explained. If in addition, contact minerals are formed in high temperature veins, and the series is continued into moderate temperature veins; and if pegmatite dikes are followed by quartz veins; and if pneumatolytic tin, tourmaline-quartz veins are closely followed by tourmaline-copper veins, and these by lower temperature silver, cobalt, lead and zinc veins, etc., as successive phases of one period of mineralization, will we not be compelled to follow the lead of the biological sciences, and adopt a natural classification of the families themselves, rather than base our classification on modifying factors?

Mr. Lindgren, however, considers that the magmatic sulphides, although the last to form, are developed within the period of consolidation of the rock, and states that they show an "embayment" structure rather than a distinctly later cross-cutting of the silicates by the sulphide veinlets, and when the definite veinlets occur, he believes that they may always be explained as the result of later alterations that have affected the ores. Following Lehmann, Weinschenck and Bergeat, Mr. Lindgren recognizes, among magmatic deposits, the type of "injected pyritic deposit" but advances no satisfactory demonstration that these were intruded as pure sulphide melts rather than as solutions.

Under "Metamorphosed Deposits" are described various kinds of deposits the origin of which is marsed by subsequent regional metamorphism.

Under "Oxidation of Metallic Ores," the related processes of oxidation, solution, and secondary sulphide precipitation are well discussed. The treatment is brief considering the immense amount of work that has been done on these subjects. The descriptions of ore deposits which have undergone important rearrangements of their metallic contents by these processes are incorporated in this chapter, and although these short summaries are excellent, the effect has been to throw these deposits out of the places they occupy in his orderly classification.

The book closes with a concise and valuable chapter on the calculation of rock analyses.

The bibliography, while not exhaustive, is excellently selected. Under each chapter or important subhead, the best literature dealing with the subject as a whole is inserted, and footnotes throughout the text assist the student in investigating any phase of the subject in which he may be interested. The reviewer believes that these references constitute the best selected bibliography of the science of ore deposits that has yet appeared, and it is to be regretted that these references are not indexed by subject and author.

The language is generally clear and concise although occasionally

marred by involved sentences. The book is not as profusely illustrated as the subject demands, and many of the illustrations chosen are the old familiar friends that have appeared and reappeared in each new book on ore deposits. The few half tones are printed on the same light paper used for the text and do not appear to good advantage. Since emphasis is laid on mineralogical descriptions, few geological maps and structural sections of the various mineral regions and ore bodies are inserted.

No review of this work would be complete without some comparison with the four other standard modern text-books on ore deposits. These are:

L. de Launay, "Traité de Metallogénie. Gites Mineraux et Metallifères," 3 volumes, 2593 pages, 1913.

Beyschlag-Krusch-Vogt, "Die Lagerstätten der nutzbaren Mineralien und Gesteine," Vol. 1, 509 pages, 1910; Vol. 2, 727 pages, 1913; Vol. 3 not yet published.

Richard Beck, "Lehre von der Erzlagerstätten," 2 volumes, 1082 pages, 1909.

Stelzner-Bergeat, "Die Erzlagerstätten," 1330 pages, 1905–1906.

All of these are more extensive treatises than Mr. Lindgren's work, although all, with the exception of de Launay's book, are confined to the subject of ore deposits, and are, with possibly the same exception, better bound and printed volumes and are more profusely illustrated.

Bergeat's work excels in that he incorporates in his descriptions of ore deposits, the ideas of the various authors, rather than attempting to establish his own views. His bibliography of the earlier literature is excellent.

Beck's revised text book should not be judged by the earlier edition known to American readers through Weed's translation. The last edition is better arranged and more complete.

Beyschlag, Krusch and Vogt's book, as yet incomplete, sets a new standard for a book on ore deposits. The discussions of the various ore-forming processes are masterly. Figures, sections, and geological maps appear in an abundance and an excellence of execution not to be found in any other text-book, and under each heading the authors suggest the application of the theory or fact presented, to prospecting and mining. One cannot criticize the omission of certain important subjects until he knows the contents of the final volume.

Finally the exhaustive work of de Launay is of interest, not only for the wealth of data incorporated, but also for the complete exposition of the speculations of this brilliant geologist. However bold his theories appear to us and however extreme the lengths to which he carries them, he has reached conclusions of great value. He has shown that ore formation has occurred in definite relation to geological history.

He has discussed the effect of depth on ore formation from more than a merely mineralogical standpoint, and has discovered, and described the chief characteristics of the main metallogenetic provinces of the eastern hemisphere.

While Mr. Lindgren's book does not compare favorably with the above-mentioned treatises in comprehensiveness, illustrations, etc., he has furnished a much needed foundation for the further development of the science in his accurate description and grouping of ore deposits in respect to their mineralogical composition, in the interpretation of the meaning of these groups by means of physical chemistry, and in the verification of these conclusions. For this reason I believe the book to be the most valuable treatise on ore deposits that has yet been written.

C. F. TOLMAN, JR.